MECHANICAL
INSPECTION

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A SURVEY
OF THE UNDERLYING PRINCIPLES AND PRACTICAL ASPECTS OF MECHANICAL INSPECTION WITH SPECIAL REFERENCE TO PRECISION ENGINEERING

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PREFACE

THERE will be many to whom it is hoped that this book will prove to be of service. In addition to those directly responsible for organizing and carrying out inspection it is believed that engineering students during, say, their third year will benefit by a study of the principles discussed and illustrated.

Whilst, naturally, the subject of inspection, with more particular reference to precision measurement, is by no means new, yet the war threw a searchlight of wider publicity upon it. Problems, for example, requiring both accuracy and interchangeability (two mutually contradictory conditions) were too numerous to mention. The result has been that more and more manufacturers have become "inspection minded."

It has been my purpose to attempt to present the general problems of inspection with as much emphasis upon the need to avoid undue severity as upon that to preserve such precision as is necessary.

One of the significant results of the war has been the increased development of the production of higher grade inspection appliances in this country. There is now available a very wide range of British precision measuring instruments of the highest quality.

I have deliberately included mention of a very wide range of testing and measuring devices. This is partly in order to allow the not widely informed reader to know the kind of apparatus which is available for various purposes and partly to use the descriptions to bring out different points in regard to fundamental inspection principles. The chapter sequence of the book has been planned so as to present the matter in as logical a manner of grouping as possible.

A chapter dealing with U.S.A. instruments has been included owing to the very close co-operation which sprang up between British and U.S.A. manufacture to strengthen the war effort. For this reason it is hoped and believed that both the U.S.A. and Britain will be increasingly interested in one another's products.

In the interests of the practical reader I have made a point of keeping the book as concise as possible consistent with fulfilling the objects which I had in view.

I have to express my thanks to many manufacturers for their great assistance in supplying detailed information and for kindly permitting me to publish such material. Due acknowledgments have been made as and where appropriate in the text.

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CHAPTER I

PURPOSES OF INSPECTION

General. The general purpose of inspection may be quite simply stated. It is to ensure that the quality of the finished product being inspected conforms to the requirements of the use to which the product is to be put. The conditions to be fulfilled should be clearly set out in a specification which may be simple or complicated according to the complexity of the product and the number of different points to which attention has to be paid. Thus the specification covering and the points to which inspection will pay attention in, say, a boot brush will be extremely simple, whereas the inspection of a battleship will be split into many departments and will be covered by many complicated specifications. The ultimate general aim is, however, the same in each case, namely to ensure that the boot brush shall do its work *as* a boot brush and that the battleship shall do its work *as* a battleship.

An important item in the general requirements will be durability, and clauses bearing on this point will, in one form or another, frequently be included in a specification. It may be that the nature of the product is such that repeated use will, after a time, cause the complete and sudden break-down; or it may be that the wear of moving parts, resulting from use, will eventually be such as to cause the overall performance to be outside the specified limits. In the former case it may be desirable to specify that a certain number of the articles or a certain percentage of the output may be tested to destruction, whilst in the latter case the specification might require that a certain percentage should survive an "age" or "usage" greater by a certain degree than the accepted minimum. In either case the materials used and the type of design employed will be such as to make possible the desirable and specified life. It should be remembered that it is often possible to relate a short test under very severe conditions to a long duration of normal conditions.

Finish. A general aspect of inspection requirement which often

gives rise to difficulty is the question of appearance or finish. This is one on which it is impossible to lay down any hard and fast rule. It may be (and indeed it often is) argued that the appearance or quality of external finish—*as such*—does not affect the *behaviour* of the product in question. This is, however, a dangerous argument. Whilst it is often true, especially in time of war, that the production of high-quality finish is a waste of man-power, there is the other side of the case. Often, the quality of finish will be one of the factors determining the suitability of the article—in which case it should, of course, be mentioned in the specification. Further than this, however, the quality of finish may easily have a psychological effect; first upon the persons making the article, causing them to suit the inside to the outside, thus prejudicing *performance*, and, second, upon the user of the article, causing him to feel a lack of faith in its excellence simply because it does not look good. This latter point is of special importance when, for any reason, the standard of appearance of an article is lowered without lowering the standard of its performance. In some cases the question of noise may come within this category. For example, it may be found that a running part, which has hitherto been fitted with a ball-bearing, can do its work perfectly satisfactorily with a plain or oil-impregnated bearing. It will often happen, however, that this will cause an increase in noise without in any sense prejudicing performance or durability or, at any rate, not beyond permissible limits. This must not, naturally, be taken to imply that there are not many cases where noise, both in magnitude and quality, is a definite indication of something being wrong. As with appearance or finish, each case must be decided on its own merits, all relevant factors being taken into consideration.

Relationship to Other Departments. Bearing in mind the fact that the main purpose of inspection is to ensure that the customer or user receives a satisfactory article, it is clear that the organization of the inspection department and the personnel carrying out the work should be distinct from the purely production side. Quite obviously, however, there must be some relationship, not only with production but also with design, and it is worth while considering some of the points in these relationships.

Whilst nobody would attempt to gainsay the fact that the inspection department must fit itself to deal with whatever is produced, it is, nevertheless, to the advantage of the "job as a whole" that the services of that department should be brought in at an early stage in

design. The design department will have as its task the problem of producing for the production department the necessary drawings, etc. It will be their endeavour to produce a design which is not merely the simplest answer to the problem with which they are faced, but to produce one which is in fact capable of being manufactured by the simplest possible organization. Whether or not it will be judged worth while to set up entirely new plant, personnel, etc., will depend upon the relative importance of the product and the quantities likely to be required. In any event the designers will have been given their guidance on these points by the general management and should be in close touch with the production officials.

It may be that it will be decided to make "one off" as a pilot model by hand-made methods in the model shop before deciding upon the final design. In this case various points of both functional and production interest are likely to emerge.

Whilst it would clearly be a case of the "tail wagging the dog" if the inspection department were to attempt to influence functional design, yet it is in the highest degree valuable that inspection officials should be in touch with what is going on at all these stages.

For one thing, it is always possible that they might be able to suggest points in design which, while not affecting either function or production, would enable more efficient inspection to be carried out. The inclusion, for example, of an otherwise unnecessary reference edge or surface might very greatly simplify the design of the necessary inspection jig or gauge and render the resulting bulk inspection an easier and speedier operation.

In addition, it will be necessary for the inspection department to make its own plans to be ready to deal with production when it commences. There will be inspection gauges and jigs to design and manufacture, personnel to train, and many other preparations to make, any or all of which may take appreciable time. The correct planning as to the stages in production at which the control of inspection is applied may well result in the saving of man and machine hours spent on work which has ultimately to be rejected for one reason or another. Equally it may be said that a careful analysis of the percentage and causes of rejection at suitable control points will often give the production department a lead as to where to seek the trouble and how to put it right.

Attitude of Inspection Staff. Whilst a member of the inspection staff should never forget that he is, as it were, an agent of the customer

or user he should always be prepared to be as co-operative as possible with the production staff. The more junior members carrying out inspection of a purely routine character will, in general, possess no right of discretion as to whether something can or cannot be just passed. The specification, instructions and gauges with which they are issued should be as clear as possible and devoid of all ambiguity so that they do not find themselves in a false position when, as may well happen, they are approached by the production foreman with an accusation of harshness. On the other hand, the more senior executive inspection staff will, in general, be empowered to exercise discretion. It is clear, however, that where such discretion is frequently applied in a particular direction there is immediate evidence in favour of reconsidering the specification in that particular direction. Thus the necessity for the use of discretion should be the exception rather than the rule.

It is very important that every member of the inspection staff should be at the greatest possible pains to know his job thoroughly. This is not merely in order to be able to do it—although, naturally, no man can do a job well unless he knows it well—but also that the production personnel whose work he is inspecting shall know it. The word of an inspection official who is recognized as knowing his job thoroughly and doing it efficiently and quietly will be accepted without question by the production side. One, however, whose knowledge is merely superficial and who covers up by an attitude of bluff and bluster will always be viewed with suspicion even when he is right.

CHAPTER II

GENERAL FACTORS AFFECTING INSPECTION

THE inspection department of a factory has duties which can be divided into three main heads. These are (1) the inspection of raw materials, purchased components, and other "goods inwards"; (2) the inspection of "work in progress" at its various stages; and (3) the inspection of the final manufactured product.

Goods Inwards. The inspection of goods inwards may, and in general will, cover a very wide range from perhaps merely counting, measuring, or weighing to highly technical and complicated tests. For example, it may be thought worth while accepting large quantities of coarse-quality nuts and bolts on only a cursory visual examination, coupled with counting or weighing to check the quantities. In addition to this a certain percentage may be subjected to a somewhat closer examination. In the case, however, of, say, supplies of steel whose physical properties are important in the purpose for which it is to be used, a much more rigorous check will be applied. It would, naturally, be impossible to test every portion; but a certain number of samples will be taken and subjected to one or more of various metallurgical tests, as, for example, tensile, torsion, repeated impact, hardness, micro-photograph, and other tests which are not within the scope of the present book, but reference to which can be made in any standard work on the subject. It may be and in a large factory it will be the case that the inspection department is equipped with the necessary apparatus and qualified personnel for carrying out this work. Under these conditions a regular routine will be established whereby test specimens are prepared, tested, reported upon, and, if thought desirable, retained suitably labelled. Adequate records will be kept and filed relating to each batch of the various types of steel—or other material—in question. In a smaller factory, however, it is probable that none, or not all, of these facilities will exist. In such a case the material may be accepted on, as it were, the good name of the supplier; but, where the quality is of importance, the purchaser will usually arrange to be provided by the supplier with the necessary certificates. These certificates will be filed, in exactly the same way as before, in the inspection department.

Where the goods inwards concerned are in the form of complete

manufactured components, such as, for example, electric switches or the like, it will be for the purchasing firm to decide whether they will depend upon the guaranteee by the supplier or whether they will apply their own functional, life, and other required tests. Here again, the inspection department should carry the responsibility and retain the relevant documents, etc. Bearing in mind what was said in the preceding chapter as to the inspector being the agent of the user, it becomes obvious that, in the case of goods inwards, the inspector is the agent of the production department, since that department is the immediate user and since it is to their interest to see that their subsequent work shall not be rejected owing to inherent defects in the quality of the materials with which they have been supplied.

Goods issued to the production side from the goods inwards store will, therefore, be regarded as carrying the guarantee by the inspection department to the production department that these goods are in all respects suitable for the uses to which they are to be put.

Work in Progress. The planning of the inspection of work in progress in all the various stages of production is, perhaps, one of the most important of all inspection duties. It is clearly necessary to preserve a balance between, on the one hand, employing an unprofitably large quantity of space, plant, and personnel on pure inspection and, on the other hand, employing too little with consequent waste owing to ultimately rejected output.

It is fair to assume that, in any but the simplest possible object, production will have been planned in such a manner that certain groups may be regarded as being more or less self-contained. The output of any one of these groups will be, so far as *it* is concerned, a complete article. This sub-product, component, piece-part, sub-assembly, or whatever else it may be termed, will be called upon to fulfil certain requirements in order to fit in with the remainder of the main job. Thus there should be an inspection of this sub-assembly in order to ensure that its imperfections do not cause a rejection of a major assembly in which it is incorporated at a later stage. The same argument may be applied to, say, a piece of metal which is to receive a number of machining operations. If an early operation is carried out badly, much time and labour will be wasted in later operations unless the imperfection is detected (and the article removed from the production line) immediately it occurs.

Still preserving the idea that the inspector is the agent of the user we see that, in these various stages, the inspector is acting

most directly on behalf of that portion of the production department concerned with subsequent stages. There will, therefore, be specifications, instructions, gauges, etc., designed to ensure that the part in question shall satisfactorily fulfil its function in these subsequent stages.

Final Inspection. If inspection has been applied to the various stages of manufacture, the possible causes of rejection of the finished product are reduced to a minimum. These possible causes will include, perhaps principally, the faulty assembly of sub-assemblies into the complete article. It may be that the various sub-assemblies operate upon one another mechanically in use so that any faulty positioning in respect to each other would cause trouble. If the frame into which they are assembled has been incorrectly drilled, bored, or otherwise machined, or if, after having been machined, the casting—if it is a casting—has warped owing to it being "green," the assembly of the various components will entail a measure of "fitting," upon the skill of which will depend the final job. If the final job is one in which the components can go together with a certain amount of loose linkage between them (as, say, in the operating levers of a typewriter) it will be comparatively simple to apply such inspection control to the manufacture of the piece parts that, providing they are within the limits of that control, they will be bound to go together without error. If, however, the mechanism is such that the final permissible limits are close, as, for example, would be the case in any precision measuring instrument, it may well be that, in addition to applying close control in the manufacture of the piece parts, a certain measure of selective assembly, together with careful fitting, is necessary to ensure the final overall accuracy.

According to the type of product and the conditions under which it is manufactured a final inspection of greater or lesser complexity will be necessary.

Location of Inspection. The actual place at which inspection is carried out is a matter of some importance, and the most desirable spot will depend upon a number of factors. If the quantities concerned are great it is essential to ensure that, whilst in no way impeding the work of the inspectors, there should be as little physical movement as possible to and from the inspection site. In the case, for example, of goods inwards in a large factory the inspection department will set up a branch near to the goods inwards store in order that the various examinations may be carried out with a minimum of transit. A

possible exception to this rule might occur in cases where highly specialized inspection of, say, a percentage of the goods in question is carried out in a department in which the character of the instruments employed demands that it be somewhat removed. Such might be the case in metallurgical or chemical examination of percentage samples. Here, however, the objection to distance of transit would not arise since, in fact, the whole bulk is not sent there, but only a comparatively small portion.

Similar considerations apply to the location of inspection of work in progress. In the case of a mass-produced sub-assembly, where, perhaps, the numbers per hour are very great, it is clearly desirable that inspection should take place in the production flow line. It will be, if possible, at the end of the production line or bench in question. For this reason it will be well that the details of physical inspection are as simple as possible, being confined to the use of simple gauges, measuring instruments, etc. To achieve this it will often be necessary to employ inspection jigs specially designed for testing the various dimensions, etc., of a particular part or mechanism. In the design of these jigs there is great scope for ingenuity on the part of the inspection department. A well-designed inspection jig, which may in itself be complicated but the operation of which is simple, may easily result in the saving of much time and material. It may, further, permit the employment, on that particular inspection, of personnel not so highly skilled as might be the case if simpler testing devices were employed.

Percentage Inspection. We have already spoken of percentage inspection and it may be well to consider for a short while what this implies. It means that, for one reason or another, it has been decided not to inspect every article but only a certain proportion of those produced. It goes without saying that those which, in fact, are inspected under these conditions should be taken, as it were, "blindfold" and not specially selected. It is, further, necessary that any group of articles submitted to test shall be related to some specific parent batch. It is necessary, in the event of certain of the tested items failing to pass test, to be able to consider in greater detail the batch from which they came. In such an event it may be decided to scrap the whole batch, or it may be decided to test a further percentage. Much will probably depend upon the previous history of that particular article.

What particular percentage shall be decided upon in any given case? It is possible to put this question in another way. How much

risk is it worth while taking, considering the job in itself and the complexity of apparatus and numbers of inspection personnel required? It is, presumably, possible, by making certain assumptions as to the value of the various constants, to evolve a mathematical formula for determining this percentage or the amount of justifiable risk. It is very doubtful whether such a calculation is worth while, however, since any experienced chief inspector will be able to decide in the light of his past knowledge just what is appropriate in a given case. Let us suppose, then, that it is decided to inspect, say, 5 per cent of a given article. The fact that the whole of the 5 per cent pass the necessary tests is no *guarantee* that the whole of the remaining 95 per cent would do so. The possibility that some would not do so can be the more readily tolerated providing that, on subsequent use or incorporation in assembly, if one is found to be faulty it can be readily rejected without consequential complications.

This subject is one which has been receiving increasing attention in recent years under the heading "Quality Control," and there are many excellent writings on this subject.

One way in which percentage inspection is sometimes given an additional guarantee is to demand that those articles actually inspected shall pass tests more rigorous than would be required if all were inspected.

Gauge versus Performance. In all inspection but, perhaps, more particularly in the inspection of the finished product, it is sometimes a moot point whether the inspection shall comprise a meticulous measurement of the physical dimensions (which, if correct, may be assumed to guarantee the performance) or whether the inspection shall comprise a careful examination *under working conditions* of the performance. Certainly where, quite apart from operation as such, certain physical dimensions have to be kept (as, for example, in an electric lamp bulb which must fit into a standard holder) physical measurement must be carried out. Where, however, this is not the case it may (and often will) be preferable to devise a series of inspection operations designed to test the article under all—or a wide range—of the conditions under which it will be used. Thus an internal combustion engine, destined for use in a motor vehicle, will be required to fulfil conditions of "behaviour" rather than of dimensions. It is true that, in its manufacture, the question of dimensions will have been very carefully watched. Each part or group of parts will have been measured either by suitable micrometer or by gauge, to ensure that it conforms

in all particulars to the design drawing and specification. Providing that all components fulfil the required dimensional tests and providing that they are correctly assembled the engine should carry out its performance tests without failure. It would be out of the question, however, to assume that this was the case without test. There will, therefore, be test rigs in which the engines may be fixed and run. Suitable "brakes" will be provided so that the running may be done under all conditions of load which the engine is likely to experience.

Temperature and Humidity. In very many cases the article may be called upon to carry out its function under abnormal atmospheric conditions. It may be that it will be called upon to carry out its duties in the tropics or in ultra-cold climates. Equally it may be that the operational conditions as to humidity cover a wide range. It is, in general, more than probable that functional operation will be affected by such conditions so that the specification will call for the fulfilment of a certain performance under abnormal conditions which will be clearly specified. In such cases it will be necessary to make arrangements for the carrying out of the tests under these conditions. It may not always be essential for the entire machine or instrument to be subjected to such control, but only a part of it. Often, however, it will happen that the whole thing or large parts of it could be affected so that, in such cases, it is necessary to make arrangements whereby functional tests (possibly on a percentage basis) may be carried out under the abnormal atmospheric conditions likely to be met. As a case in point may be mentioned the "tropical ovens" manufactured by Messrs. Belling & Lee, Ltd. In these ovens, the interior of which measures about 30 in. by 18 in. by 18 in., articles may be subjected to 100 per cent humidity at a temperature which is thermostatically controlled within a few degrees of, say, 140° F., representing somewhat severe tropical conditions. Where larger space is required it is necessary to construct special rooms or chambers for the purpose. Similar considerations apply to conditions of cold. It may, in many cases, be thought sufficient to subject only the first few of any new design to tropical or other abnormal tests and, if they pass these satisfactorily, to assume that all of the production will be satisfactory.

Specifications and Test Sheets. It is the duty, naturally, of the department calling for the manufacture of a given article to lay down the functional requirement. This will, essentially, be in the form of a statement as to the *performance* which it has to give. The design

department (if the idea has not originated there) will convert this general performance statement into greater technical detail for the guidance of the actual designers engaged on the work. It will, however, normally be for the inspection department to draw up the official specification or specifications and to settle the question of what tests are to be applied throughout and at the conclusion of manufacture. Any special conditions which have to be met, e.g. tropical, etc., will be mentioned in the specification with a reference to the tests considered appropriate to the case. Attempts have been made to standardize, so far as possible, these abnormal requirements. The three fighting services have, for example, made attempts to co-ordinate the temperature range through which equipment must function satisfactorily. There is a fairly clear specification as to the atmospheric cycle represented by the phrase "Tropical Conditions." There has up to the present been no actual standardization of the conditions which may be regarded as "free from mould growth"—a serious trouble encountered by many substances in the tropics—but the School of Tropical Medicine has carried out many tests on behalf of the Services.

Where standard specifications exist, it will naturally be sufficient for the inspection department merely to mention the appropriate number or numbers. These will frequently be British Engineering Standards (B.E.S.A.) specifications, since that association has done and is doing much to assist standardization throughout the engineering industry. It is, of course, the duty of all designers to take the utmost pains to see that, so far as possible, all components employed in the design shall fall under one or other of the standard specifications. Nothing presents more difficulties of manufacture than points of design which are not standard.

The specifications issued by the inspection department should make reference—even if only in general terms—to the appropriate test sheets employed. The careful compilation of a test sheet is every bit as important as the designing of the tests themselves. A good test sheet will, so to speak, leave nothing to chance. It will ensure that the operative who actually carries out the inspection does not overlook any particular point. It will constitute a record of the "as manufactured" behaviour of the article to which it refers and, in the event of the percentage rejection of a given article being high, it will enable the works management to analyse the probable causes of the error in production and to correct them.

It is almost impossible and might indeed be misleading to attempt

to lay down any details as to the compilation of test sheets in general. Their characters must differ enormously according to the types of article whose inspection they cover, but we can see, in the light of what we have said above, that certain broad essentials should be fulfilled.

The size and shape of the form should be such that it is easily filed so that reference to it is simple.

The heading should clearly set out the name of the article being tested, its manufacture, serial number, and the date of the test.

Those items requiring only visual inspection or inspection by "feel," e.g. the smoothness of movement of an operating mechanism, should be clearly stated even though the report remarks column receives only a $\surd$ to indicate that the item is satisfactory. This will ensure that "familiarity does not breed contempt" and that no item goes by default.

Each item requiring measurement (or gauging by fixed gauges) should be clearly set out with appropriate columns to insert the necessary observations. If definite measurements have to be taken there should be a column not only for the reading itself but also for the error or departure from normal. It is, further, desirable that the limits or tolerance be stated on the form. If the test is by simple "go" and "no-go" fixed gauge the entry should show a $\surd$ if correct or should state which way the error is (i.e. too large or too small) if incorrect.

Where there is a question of performance in which there will be, say, a dial reading as a result of a given setting it will in general be sound to decide beforehand the different settings at which readings are to be taken. These will be printed in the test sheet and against them will be printed the true reading which should be obtained at that setting. There will then be a column in which the actual reading is entered or, if there is possibility of backlash, as will generally be the case, two columns, one for readings "increasing" and one for readings "decreasing." There should be an additional three columns showing the departures of these readings from "true," i.e. "error increasing" and "error decreasing," and also the difference between the readings, i.e. "backlash." Here again the permissible limits or tolerance should be clearly stated.

The points to be covered in the tests should be chosen so that not only do they give a clear picture as to the behaviour of the article but that they also permit a ready reference back to the "manufacturing" cause of any errors which exist.

One last general point should be mentioned in this connection. Differences of view exist as to whether it is preferable to show a series of readings in the form of a "table" or as a "curve" drawn on squared paper. There is no question that, providing the scales are suitably chosen, a curve gives a very clear indication of general tendencies such as is not given so clearly by a mere table of figures. On the other hand, where several sets of figures are concerned, it sometimes presents a somewhat confused picture to attempt to show these all on one graph. The best answer is probably to arrange that the main report shall be given in the form of tables, and that a curve of only, say, the "increasing" errors be attached. If there should be evidence of trouble requiring further investigation, further curves may be drawn from the tabled figures as may be thought necessary.

CHAPTER III

ACCURACY

Observation. Since it is true to say that the most important aspect of mechanical inspection concerns the making of measurements of all kinds, it is well worth while devoting some little attention to the question of accuracy and the various factors affecting and affected by it. From the point of view of making measurements the human body is a relatively poor instrument. Thus, unaided by some form of instrument, it is very difficult indeed to estimate a length, judge a weight, or assess a time interval any more closely than within very wide limits and two people's estimates of the same thing may vary by a very large amount. In estimating, for example, a length of a few inches we are trying to carry in our "mind's eye" a picture of one inch and guess (for it is little more) how many of such lengths are contained in the one which we are trying to estimate. Similar ideas apply to other measurements, such as weight, time, etc. Man has, however, by his ingenuity and craftsmanship succeeded in developing machines and instruments of all kinds whereby his "guesses" may be translated into more or less exact measurements.

Whilst in some few cases the sense of hearing or that of touch may be used, most mechanical measurements call upon the sense of sight. This sense, or the brain behind it, can usually recognize coincidences, as of a pointer on a scale graduation, more readily than it can estimate proportions of subdivisions. Thus, if great accuracy is required, a scale will usually be provided with a Vernier as described in Chapter VI. This is merely a device whereby a "recognition of coincidence" is substituted for the "estimating of a proportion." Sometimes the reading of an instrument depends upon the recognition of a "threshold effect" as, for example, the fact of a pointer *just* or *just not* moving.

Impossibility of Absolute Accuracy. We often hear mention of something being "absolutely accurate" or may be "dead accurate." Let us see what, if anything, this means. Suppose we go to a grocer's shop to buy a pound of tea. Do we get a pound of tea or do we get a few tea leaves too few—or too many? Further, can we know whether or not this is the case? There are various factors which enter into this. There are the scales employed, which will usually not show any visible difference whether or not there are tea leaves too few or too

many. There is the position in which the grocer stands and whether or not his observation of the pointer is done in such a way that there is an error of "parallax." There is the grocer himself, who may, consciously or unconsciously, wish a reading to be biased one way rather than another. All these factors constitute sources of error as a result of which the amount of tea which we receive will differ by a greater or lesser *unknown* amount from the pound which we want. The magnitude of some of the errors could be ascertained with the means there available. That of others could not. Thus it would be simple for the grocer to ensure that he stood in such a position as to avoid parallax. We could check his observation of the pointer to ensure that there was no introduction of unconscious bias (taking care that we ourselves did not attempt to introduce it!). Also we could make several weighings of the same quantity and take the average result. In spite, however, of all these precautions there would still be certain fundamental errors unknowable with the means at our disposal in the shop.

Or, to take another example, consider the case of timing a motor car in its travel over a given distance by means of two stop-watches held respectively by people at each extremity of the measured distance. A large number of errors can enter into this, of which the following are the more obvious—

The distance may not be accurately measured.

The observers may not operate their watches when the same portion of the car is passing the mark.

The first observer may not signal *exactly at the instant* that a particular portion of the car passes the first mark.

The second observer may not operate his watch *exactly at the instant* that the signal is made.

All these and other unavoidable errors combine to make such a measurement—and the resulting estimate of speed—an extremely inaccurate affair.

On the other hand, there are instruments of many kinds capable of being used to make far more exact determinations of measurement. For example, in astronomical measurements of distance it is by no means out of the question to keep the errors to less than one part in a hundred million. It is possible, by suitable means, to measure weight with errors of less than one part in two hundred and fifty million. In terrestrial survey work it is easily possible to measure distances with errors no greater than an inch in the mile. In every case, however, there will still be unknown and unknowable errors.

Sensitivity and Consistency. In attempting to achieve greater and greater degrees of accuracy the instruments employed will, of necessity, be increasingly sensitive. An instrument cannot be more accurate than is permitted by its degree of sensitiveness. The definition of sensitivity may be taken as being the following ratio—

$$\frac{\text{Change of instrument indication}}{\text{Change of quantity being observed}}$$

Thus, the greater the change of indication for a given change of observed quantity, the greater may be said to be the sensitivity of the instrument. It will be realized that the degree of sensitivity of a given instrument is not necessarily the same all over the range of its readings.

Another consideration, which is of importance where accuracy is desired, is that the readings obtained when observing a given quantity shall be as nearly as possible all the same. A highly *sensitive* instrument is not necessarily *consistent* in its readings and, clearly, an inconsistent instrument cannot be accurate to a degree better than its inconsistency.

Whilst it is true, therefore, to say that an instrument of great accuracy will, in general, possess great sensitivity and consistency, it is not true to say that an instrument which is sensitive and consistent is necessarily accurate. Its readings may, for example, be taken from an engraved scale which is all wrong. The errors, however, in such an instrument would, at any given reading, be constant, so that it would be quite possible to *calibrate* it, that is to say, to determine the error of the instrument at every reading and to set out these errors in the form of a curve or table. This would permit the addition or subtraction of the appropriate error at any given reading. The accuracy of the result depends, naturally, upon the accuracy with which the various errors may be determined. In the foregoing it is, clearly, presupposed that there is available, for determining the errors, another instrument whose accuracy is greater than the one with which we are concerned.

Sources of Error. In the attempt to achieve accuracy there will almost invariably be incorporated in the instrument some device designed to magnify a portion of the observed article or, at any rate, its effect upon the instrument. Such magnification may be achieved by either optical or mechanical means, but in any case it carries with it its own inherent inaccuracies.

A lens system may distort in a variety of ways. It is beyond the

purpose of this book to go into the intimate detail of optical systems employed in mechanical inspection. As an example, however, we may mention the examination of form by projection. An apparatus employing this principle is described in a later chapter, but we may say that, in essence, a magnified picture of the article under examination (say the tooth form of a spur gear) is thrown on to a screen and there compared with an enlarged drawing exactly to scale of what the article ought to be. The success or otherwise of this method is naturally dependent upon the fidelity with which the lens system can produce an image which is a true (though magnified) picture in every respect of the article being examined. This will most certainly not be the case if the lens system is not a good one and if there are various inherent errors which have not been corrected. It is essential, therefore, in using such an instrument, as indeed in using any instrument, to ensure that its inherent inaccuracies are not greater than can be permitted in regard to the work it has to do.

With a mechanical magnifying system there are other sources of inherent error. If a system of levers is employed there are such things as the bending of the levers, backlash at the pivots, etc. If lead-screws or worms and worm-wheels are used there are errors in pitch of various kinds to be considered. In addition to these there is always the question of distortion of the whole instrument whether owing to age or to atmospheric conditions.

It is therefore clear that, with any magnifying system, the employment of magnification produces greater facility in observation with consequent greater accuracy *only providing* that the errors inherent in the magnification are not greater than the increase in accuracy at which we are aiming.

In the *Dictionary of Applied Physics* Mason suggested that an accurate measuring instrument should, if possible, fulfil the following seven conditions—

1. It should possess the requisite accuracy.

2. It should have constant accuracy.

3. Every important source of inaccuracy should be known.

4. Any errors should, so far as possible, be capable of elimination by adjustment.

5. This adjustment should be possible without the addition of other special apparatus.

6. When an error cannot be eliminated it should be made as small as possible.

7. When an error cannot be eliminated it should be capable of measurement by the instrument itself without external apparatus so that results may be corrected.

So far as instrumental errors are concerned, therefore, we can sum up by saying that they should be kept as small as possible, and that those that remain fall into two classes. One of these classes of error is constant and knowable so that, possibly by aid of external apparatus, the instrument may be calibrated and the errors taken into account when using it. The errors of the other class are unknowable and, possibly, variable, so that, in taking any observation, the true value lies within certain plus and minus departures from the observed value and cannot be tied down any more closely than that.

It will have become apparent that, whereas a simple measurement, where no close accuracy is required, may be made with very simple apparatus, we shall be forced to introduce more and more complications as we demand more and more accuracy. Each additional complication will almost invariably carry with it its own sources of error and, although these may be less than the major errors which the complication is designed to eliminate, it is true to say that the greater the accuracy required the greater the **number** of **sources** of error to be investigated and controlled. As accuracy is increased these additional sources of error will probably become more and more subtle in character.

Geometric Design. A very important point which has to be watched in all instrumental design is distortion. This, if constant, would perhaps not be a serious disadvantage, and, indeed, every structure is strained by the forces acting upon it, including gravity. Strains which, however, are variable and which cannot be controlled require to be avoided so far as possible. This latter class of strain or distortion can be caused by movement of, say, a frame casting due to the gradual removal of internal stress with age. It can also be caused by inherent stresses set up by faulty design. To avoid the former cause it is necessary that any castings, etc., which are employed should be adequately "aged" according to the best accepted treatment. The avoidance of the latter is, naturally, a matter of design.

Clerk Maxwell was, in 1876, the first writer to give theoretical consideration to the fundamentals of instrument design, and to point out that every rigid body has six degrees of freedom of motion, namely three directions of translation mutually at right angles and three directions of rotation about axes mutually at right angles. If a body is

held or constrained in more than six ways it will be the subject of internal stress. It can be subject to internal stress, even though it retains certain degrees of freedom, if it be held in any number of ways (even less than six) two or more of which are redundant to one another. The case most frequently quoted is that of a stool or table. If it be supplied with only three legs it loses three degrees of freedom, namely one translation (vertically, since we assume that its weight keeps it *down*) and two rotations (about horizontal axes). It retains two translations (in horizontal directions at right angles to one another) and one rotation (about a vertical axis). If it be fitted with a fourth leg, either one of the legs will not operate or else elasticity will permit all four legs to bear on the floor, in which case there is redundancy of constraint and strain is set up. The subject of geometric design is one to which special study should be given, but this is not the appropriate place. We are concerned rather with the *use* of measuring instruments than with their *design*. Nevertheless it may not be out of place and may be helpful to mention one or two illustrations of geometrical design.

A well-known and convenient method of resting an instrument on a stand is as follows. The instrument is provided with three approximately hemispherical feet. The stand accommodates these feet as follows. One rests in a hole in the form of an inverted pyramid, i.e. trihedral, thus providing three points of contact. One rests in a V groove, pointing roughly towards the hole, thus providing two more points of contact. The third rests on the plane surface of the stand. In another, and perhaps more usual, form the stand consists of three V grooves arranged radially at approximately 120 degrees to one another. In each of the above cases it will be seen that the position of the instrument on the stand is exactly determined. That is to say, it may be removed and, when replaced, will occupy the same position as before. At the same time there is no redundant control and, therefore, no strain.

Another example of geometric design is the form of slide employed in many measuring instruments, as, for example, measuring microscopes. This is shown schematically in Fig. 1. The base consists essentially of the cylinder A and the surface C. The plane of C should be parallel to the axis of A for instrumental accuracy, although small departures from parallelism do not affect the *geometric* structure. The sliding member is supplied at one end with two inverted V grooves which rest on A. The other end rests on C. Assuming that gravity holds the sliding member down to the base, there is only one direction

of freedom, namely parallel to the cylinder A. In that crude form, however, the apparatus is not quite geometric, there being four line contacts (two at each of the V grooves) and one surface contact. A perfectly geometric design is achieved, however, by having a small hemispherical stud on each of the four surfaces of the V grooves, and a fifth on the under side of the end in contact with C. (This fifth point is indicated by D.) This gives us five *point* contacts with perfect control and perfect freedom from strain for any slight departures from truth in either A or C.

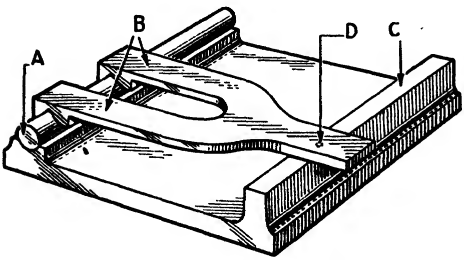


FIG. 1. GEOMETRIC SLIDE

The foregoing considerations are perfectly satisfactory so long as no heavy loads have to be carried by the points of contact. If, however, such loads are heavy, as will usually be the case in large apparatus, wear would become excessive. Much can be done by such means as self-aligning bearings, ball and socket joints, etc., to overcome the difficulty but, in general, it will be necessary to depart to some extent from perfectly geometric design and to use well-fitted line or even surface contacts in certain parts.

One final point needs to be noted in regard to geometric design, and that is that there must always be a positive (and preferably constant) force tending to maintain closure of the contact points. Such force may be supplied by gravity, by means of a spring, or by means of auxiliary points of contact.

What Accuracy is Needed. In all the foregoing we have been considering matters as though we desired to achieve the utmost accuracy which lies within our power. But is this necessarily the case? To return to our pound of tea, does it really matter in that case whether or not we get tea leaves too few—or too many? To be more accurate than we are in such a matter would require accurate weighing apparatus, skilled staff, and skilled inspection supervision, so that the cost and complication would be out of all proportion to the doubtful advantage gained. On the other hand, if it is a question of, say, making accurate survey measurements, where the cost is not important compared with the accuracy of our information, we shall employ the most accurate theodolites, etc., which we can obtain, and shall arrange

for highly skilled operators to use them. In other words, the accuracy which we shall try to obtain in any given case will depend entirely upon what is regarded as desirable in that case, and any attempt to obtain greater accuracy must be related to the cost and complications entailed in obtaining it.

Build-up Inaccuracies. In any built-up mechanism there will usually be conditions whereby a number of possible slight errors present in each of the separate components would, *if they all existed together*, build up into a large overall inaccuracy. On the laws of probability, however, it is in the highest degree unlikely that the maximum errors will occur simultaneously in all components. The most general practice under such conditions is to take, as the *probable maximum* total error, the square root of the sum of the squares of the separate possible maximum errors.

General Conclusion. We see, from what has gone before, that there can be no such thing as perfect accuracy, and that there is no instrument capable of telling us whether or not we have got it. Such phrases as "dead accurate," "spot on," "dead right," etc., become meaningless and of only relative value. We can, by taking many precautions, make our errors—and the errors in our measurement of them—extremely small; but, the smaller we try to make them the greater becomes the complication of our task and, with this increased complication, the greater the number of possible sources of error of which we must take care. Finally, the accuracy at which we aim, that is to say, the trouble to which we go to avoid errors in manufacture and in measuring those errors during inspection, must depend upon the job itself and on the nature of what is required.

CHAPTER IV

DEFINITIONS OF TERMS

In order to avoid any confusion or misunderstanding, a number of terms met in the workshops and inspection department are given below, together with brief explanations of their meanings. Although perhaps, strictly speaking, these should have been given in alphabetical order, yet, since the number is comparatively small, the different terms are given in a more logical sequence.

GENERAL INSPECTION TERMS

Dimension. The size given on a drawing or in a specification to any particular feature of a piece of work; such as a length, a diameter, etc.

Limits of Size, or Limits. Dependent upon the requisite accuracy of the finished work, use will be made by the manufacturer of a certain quality of machine and skill of operator. It is realized that, however good these may be, there will, in production, be certain departures from any stated dimension. Limits are accordingly set to these possible departures and these are expressed as (high and low) sizes near to the given dimension and between which the finished work must lie.

Open Dimension. This is a dimension for which no limits are specified on the drawing. In such a case it is understood that the manufacturer will work to the commonly accepted standard limits applicable to such cases. Thus, in certain classes of instrument work for example, an open dimension implies that the work is to be kept within limits respectively 5 thousandths of an inch greater than and less than the stated dimension.

Basic Size. The most usual manner of expressing limits is to give a size, which is known as the basic size, and to state the amounts by which the work may exceed or fall short of this basic size. In this case it will be seen that the limits are expressed as limits of variation, e.g. 3·5 in. $\begin{smallmatrix}+\ 0{\cdot}002\\ -\ 0{\cdot}003\end{smallmatrix}$ means that the work must lie between 3·497 in. and 3·502 in.

Actual Size. This is the actual measured size of the work as manufactured.

Nominal Size. The size of a dimension by which convenient reference is made to it. It will usually be in "round figures" and not necessarily exactly equal to the basic size.

Tolerance. The amount of variation in size of a given dimension which can be **tolerated** in the finished work. Thus, for the dimension quoted above, viz. $3{\cdot}5\text{ in.}\ {}^{+\,0{\cdot}002}_{-\,0{\cdot}003}$, the tolerance is 0·002 in. *plus* 0·003 in. or 0·005 in.

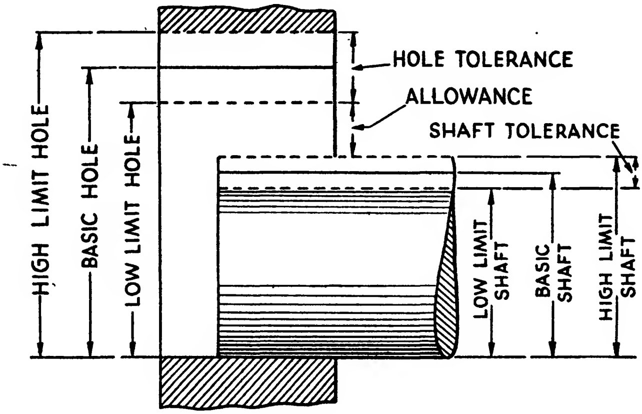


FIG. 2. SHAFT AND HOLE, TERMS USED

Limits of Tolerance. These are the amounts of variation from basic size which may be permitted. They must have their appropriate algebraic sign and in the example above are seen to be + 0·002 in. and — 0·003 in. As we have stated, this is the most usual method of stating limits. It is sometimes the case that one or other of these figures may be zero, meaning that no variation of size **in that direction** may be permitted.

Allowance. This is by no means the same thing as tolerance. It has reference to the case of two "mating" components, one of which has to fit inside the other. It usually refers to shafts in holes and indicates the difference between the size of the hole and the size of the shaft. Although it is clear that, where both shaft and hole are given tolerances, there will be high and low limits to the allowance, we usually indicate by this term the **minimum** difference between shaft and hole, that is to say, the difference between the minimum hole and maximum shaft. Fig. 2 indicates allowance and tolerances of a shaft in a hole.

Fit. This indicates the amount of play (which, as will be seen in Chapter VIII, may be **negative** in value) which is present when two "mating" parts (e.g. a shaft and hole) are assembled together. Classes of fit will be discussed in Chapter VIII.

Hole Basis. A system in which limits of shaft size are related to a constant basic hole dimension.

Shaft Basis. A system in which limits of hole size are related to a constant basic shaft dimension.

Unilateral System. A limit system in which the **basic** dimension coincides with the dimension of one of the limits, usually the lower.

Bilateral System. A limit system in which the limits are disposed one greater than and one less than the basic size.

Plug Gauge. A gauge in the form of a short cylinder or plug whose diameter is equal to that of the hole which it is designed to gauge.

Ring Gauge. A gauge in the form of a ring whose internal diameter is equal to that of the cylinder or shaft which it is designed to gauge.

Gap Gauge. A gauge in the form of a horse shoe (or something like it), the gap between the ends being passed over the work which it is designed to gauge.

Limit Gauge. In effect two gauges in one, as, for example, a double-ended plug gauge or gap gauge. This form of gauge is made to limits one of which permits the gauge to pass into or over the work and the other of which does not. Such a gauge is sometimes called a "go and not go" gauge.

SCREW THREAD TERMS

Single-start Screw Thread. The ridge formed on a cylinder or cone by cutting a continuous groove or helix in such a manner that it advances at a uniform rate in an axial direction as it rotates round the cylinder.

Multiple-start Screw Thread. The ridges formed on a cylinder or cone by cutting two or more grooves as above described equally spaced from one another in an axial direction.

External Thread. The thread on the outside of a member, e.g. the thread on a bolt.

Internal Thread. The thread formed on the inside of a member, e.g. a nut.

Crest of Thread. The ridge, i.e. the part farthest from the parent metal in which it is cut. (See Fig. 3.)

Root of Thread. The bottom of the groove formed between two neighbouring ridges. (See Fig. 3.)

Flanks of Thread. The two sloping side surfaces which connect roots and crests. (See Fig. 3.)

Depth of Thread. The radial distance between crest and root. (See Fig. 3.)

Fundamental Triangle. The triangle formed by the extension of the thread flanks. (See Fig. 3.)

Apex. The imaginary point of intersection of the extended flanks on either side of a crest. (See Fig. 3.)

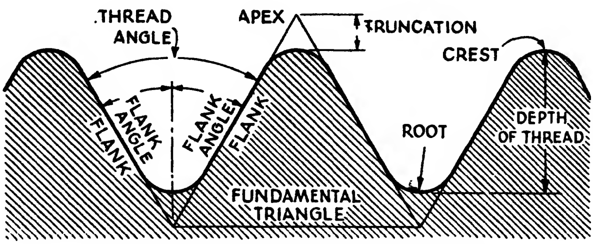


Fig. 3. Screw Thread, Terms Used

Truncation. The radial distance between crest (or root) and apex. (See Fig. 3.)

Angle of Thread. The angle between the flanks measured in a plane passing through the axis. (See Fig. 3.)

Flank Angles. The two angles between individual flanks and a line perpendicular to the axis. (See Fig. 3.)

Pitch. The axial distance between the crests (or roots) of neighbouring threads.

Lead. The distance which a nut would advance axially for one revolution.

N.B. For a single-start thread the pitch and lead are the same. For a multiple-start thread with n starts the lead is n times the pitch.

Major Diameter. The diameter of a cylinder which would just touch the crests of an external or the roots of an internal thread.

Minor Diameter. The diameter of a cylinder which would just touch the roots of an external or the crests of an internal thread.

Effective Diameter. The diameter of a cylinder which would cut the surface of the thread in such a manner that the intercept between neighbouring flanks is equal to half the pitch.

Mean Helix Angle. The angle made by the plane of the flank at the extremity of an effective diameter with a plane at right angles to the axis.

GEAR TERMS

Base Circle. The circle from which the involutes of the teeth are constructed. (See Fig. 4.)

Root Circle. The circle on which the roots of the teeth lie. (See Fig. 4.)

Pitch Circle. The circle where meshing contact of roll without slip should take place. (See Fig. 4.)

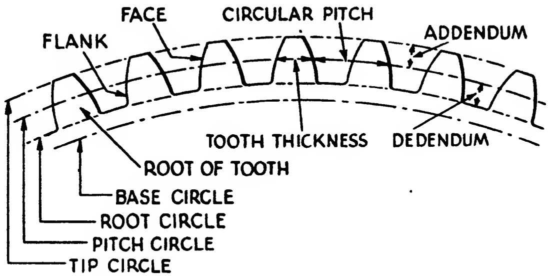


Fig. 4. Spur Gear, Terms Used

Tip Circle. The circle on which the tips of the teeth lie. (See Fig. 4.)

Tooth Flank. The portion of the side of the tooth within the pitch circle. (See Fig. 4.)

Tooth Face. The portion of the tooth side outside the pitch circle. (See Fig. 4.)

Tooth Thickness. The circumferential thickness of the tooth measured at the pitch circle. (See Fig. 4.)

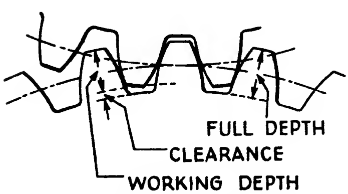


Fig. 5. Spur Gears Meshed, Terms Used

Circular Pitch. The circumferential distance between corresponding points on adjacent teeth measured on the pitch circle. (See Fig. 4.)

Addendum. The radial distance of the tip of the tooth from the pitch circle. (See Fig. 4.)

Dedendum. The radial distance of the root of the tooth from the pitch circle. (See Fig. 4.)

Clearance. The radial distance between the root of the tooth and the tip of a mating tooth when in fullest mesh. (See Fig. 5.)

Module. The pitch diameter divided by the number of teeth.

***Diametral Pitch** (D.P.). The number of teeth divided by the pitch diameter.

* This is more frequently used than Module.

Backlash. The shortest distance between the non-driving surfaces of adjacent teeth in mating gears.

Pressure Angle. The movement of the point of contact of the pitch circles of a pair of mating gears will make an angle to the common tangent at that point. This angle is called the Pressure Angle. It is very often 20°, but is sometimes 14½°.

BEVEL GEARS

These are used when it is required to transmit power between two shafts which lie in one plane and whose axes intersect. The action is as though the drive were transmitted between two cones whose apices meet at the theoretical point of intersection of the shafts, whose surfaces make a line contact, and the ratio of whose angles is made to be equal to the desired gear ratio. (See Fig. 6.)

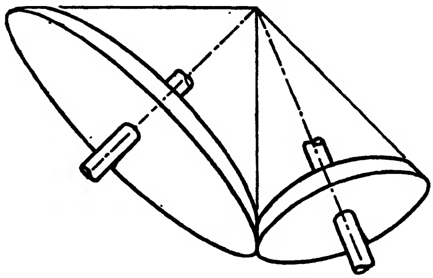


FIG. 6. BEVEL GEAR PRINCIPLE

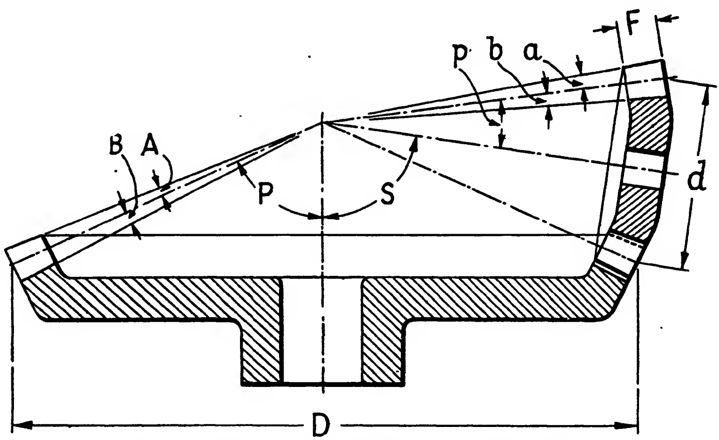


FIG. 7. BEVEL GEARS MESHED, TERMS USED

The teeth will be cut so that their direction, as it were, points in the direction of the common apex. Fig. 7 shows a pair of bevel gears in mesh and the more important dimensions concerning them.

Shaft Angle. *S*. The angle between the axes of the wheel and pinion shafts.

Pitch Angles. *P* and *p*. The angle between the axes and the pitch lines of the teeth.

Pitch Diameters. *D* and *d*. The distance between the external ends of two diametrically opposite teeth measured at the pitch line.

Addendum Angles. *A* and *a*. The angle subtended at the apex by the addendum.

Dedendum Angles. *B* and *b*. The angle subtended at the apex by the dedendum.

Face Width. *F*. The length of the tooth measured along a line passing through the apex.

SPIRAL BEVEL GEARS

These gears are used under conditions similar to those of straight bevel gears, but the shape of the teeth is different. They are curved instead of straight and, in point of fact, tend to displace straight bevel gears owing to the facts that they are easier to produce and are quieter in action.

SKEW GEARS

When it is required to couple together two shafts which do not intersect and do not lie in the same plane, the type of gearing employed is known as skew. There are various types of skew gear, and a study of the different types is beyond the purpose of this book. It suffices to say that, though these types differ in construction, they are all more or less identical in principle, which may be represented as two cylinders rolling on one another. (See Fig. 8.) The axes of these cylinders coincide with the axes of the shafts in question, and their point of contact lies on the line drawn along the shortest distance between the shaft axes. The gear ratio is the ratio of the diameters of the two cylinders.

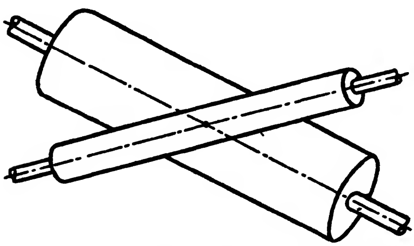


FIG. 8. SKEW GEAR PRINCIPLE

The worm and worm wheel form of gearing is a particular case of skew gear.

CHAPTER V

STANDARDS OF MEASUREMENT

Workshop and Inspection Gauges. Let us return for a moment to the grocer's shop which we mentioned early in Chapter III. We may, for our present purpose, regard it as a factory where the raw material is tea in bulk and where the manufacturing process consists in parcelling the tea into one-pound packages. The scales which the grocer uses correspond to his "gauge" and, quite apart from any question of his skill in using them, it is, as we saw, important that the scales themselves must not possess an error greater than can be permitted under the conditions of the case. We can imagine the scales carrying a pointer which passes in front of a fixed plate on which there are two marks. If the pointer is to one side of these two marks the package is too light, if it is to the other side the package is too heavy, whilst if it lies between the two marks the package is within the limits permitted, bearing in mind the supposedly known errors of the scales and supposing that these errors do not increase.

We may easily translate this idea to a factory. Suppose that a particular process consists of a turning operation in which the finished diameter is to lie within the limits, say, 0·997 in. and 1·002 in., which we can regard as being 1 in. plus 0·002 in. minus 0·003 in. We should not normally supply the operator with a micrometer gauge in such a case but with two gauges, one of which would be made to be 0·997 in. and the other one 1·002 in. In practice these would both be incorporated in one article whose jaws were nominally 1 in. apart, but actually one of them would have a step giving two gaps, the outer one of which would be 1·002 in. and the inner one 0·997 in. In passing such a gauge over the work the outer gap should pass over it, thus showing that it is less than 1·002 in., whilst the inner gap should not pass over it, thus showing it to be greater than 0·997 in. Such a gauge is called a "go and not go" gauge, and will be a workshop gauge for the use of the operator performing the operation.

It is important, however, to ensure two things. One of these is that the workshop gauge is correct and has not got out of truth, and the other is to ensure that the operator has used his gauge correctly. The work therefore passes at some stage or other, determined by such considerations as those in Chapter II, through the hands of an

inspector, or examiner as he is sometimes called. This inspector, or examiner, will be equipped with a gauge, possibly a micrometer, but more probably another "go and not go" gauge, which constitutes a check on the workshop gauge—as well as on the operator. This latter gauge is classified as an inspection gauge.

Limits for Gauge Dimensions. We have discussed the fact that there is no such thing as "absolute accuracy," so that we are forced to realize that, in the gauge itself, we must permit a tolerance on the stated dimension. What should be this tolerance? In Fig. 9 let AB

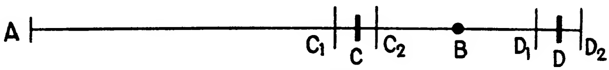


FIG. 9. LIMITS

represent a dimension which we are to gauge. Suppose that the limits which may be permitted to this dimension are AC and AD. We should thus try to make a "go and not go" gauge with AC as the "not go" (assuming that AB is an *external* dimension) and AD as the "go" gauge. But these gauge dimensions themselves must each be given limits, which we may suppose to be AC_1 and AC_2 for the former and AD_1 and AD_2 for the latter. This means that we may be limiting our work to lie between AC_2 and AD_1, or we may be permitting it to lie between AC_1 and AD_2, and we do not know which. On the one hand we are unduly penalizing it, whilst on the other hand we are giving it too much liberty.

It is true that we could guard against giving too great a tolerance by arranging that the low limit of the "not go" gauge should coincide with the point C, whilst the high limit of the "go" gauge should coincide with the point D. But this would have the effect of pushing the point C_2 farther to the right and the point D_1 farther to the left. Thus, although we had ensured that we did not exceed the permitted tolerance, we should not know whether or not we had unduly restricted it.

The effects which we have discussed above become more and more marked the greater the amount of tolerance which we permit in our gauge. If, on the other hand, we restrict this tolerance too much we are up against difficulties of gauge manufacture. A fairly comprehensive set of gauge limits has been laid down by the British Standards Institution for a wide range of conditions. Thus for work, say a shaft diameter, to which a tolerance of 0·005 in. has been given, the gauge tolerance is 0·0005 in. For work with a tolerance of 0·05 in. the gauge

tolerance is 0·004 in. The exact ratio varies, but a very good working rule for gauges (as, indeed, for any inspection equipment of a more complicated character) is that the tolerance on the gauge dimension (or other inspection instrument) should not be greater than about one-tenth of the tolerance on the work.

Relationship Between Workshop and Inspection Gauges. Unless attention were paid to the matter it could very well happen that an inspection "not go" gap gauge is on the low limit, whilst the corresponding workshop gauge is on the high limit. The result of this would

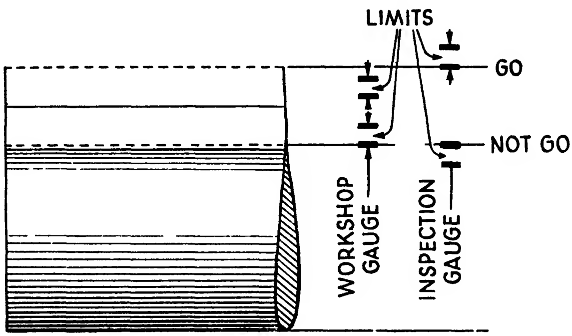


Fig. 10. Gauge Limits

be that work which was quite correctly passed by the workshop gauge would be rejected by the inspection gauge, or vice versa. It is important, therefore, to ensure that the limits set to workshop and inspection gauges respectively shall be adjusted with respect to one another. Taking gap gauges—for the inspection of "solid" work—as an example, the limits set for the "not go" inspection gauge are at smaller dimensions than those set for the workshop gauge. Thus any work rejected by the workshop gauge, being bigger than its dimension, must be bigger than that of the inspection gauge and, as a consequence, must be rejected by it also. Conversely, the limits set for the "go" inspection gauge are at greater dimensions than those of the workshop gauge. Thus any work over which the workshop gauge passes will certainly be within the dimension of the inspection gauge. Since wear with use is in each case in the direction of increasing the dimension, it is fair to assume that these conditions will persist, more especially when it is remembered that wear is likely to be more rapid with workshop than with inspection gauges. These conditions are shown diagrammatically in Fig. 10.

As examples of the above we may take the cases, already quoted, of work whose tolerances are 0·005 in. and 0·05 in. respectively. We have seen that the tolerances on the gauges for this work are, respectively, 0·0005 in. and 0·004 in. These tolerances apply equally to workshop and inspection gauges, but are disposed differently and are set out in Table I.

TABLE I*

CERTAIN LIMITS FOR RING AND GAP GAUGES (INCH UNITS)

Work Tolerance	Gauge Tolerance	Limits "Go" Gauge		Limits "Not go" Gauge	
		Workshop	Inspection	Workshop	Inspection
0·005	0·0005	− 0·0002 − 0·0007	+ 0·0005 0	+ 0·0005 0	0 − 0·0005
0·05	0·004	− 0·001 − 0·005	+ 0·004 0	+ 0·0045 + 0·0005	0 − 0·004

The dispositions of these values should be compared with one another with reference to Fig. 10.

Similar figures are laid down for wide ranges of "work" conditions in the appropriate British Standards Institution Specifications, which include not only plain plug and gap (or ring) gauges but also those for screw threads, to which similar principles apply.

Gauges for Mating Parts. Although not of exactly the same character as the foregoing, a careful study of that and the principles with which it deals will show that similar considerations must be applied in the setting of limits on gauges for parts which are required to "fit together." The limits on the gauges for internal and external parts respectively must be so related that these parts go together with little or no "fitting."

Reference Gauges. Although the inspection gauges constitute a control upon the workshop gauges, yet even these former may deteriorate or vary for one reason or another. It is, therefore, important that there should be available some method by which the inspection gauges may themselves be measured or else accurately compared with others whose correctness is beyond question. Such gauges will be known as reference gauges. Their dimensions should be known to a high degree of accuracy, they should be used but seldom and the

* Abstract from B.S. 969, "Tolerances for Plain Limit Gauges," by permission of the British Standards Institution, from whom official copies of the specification may be obtained, price 2s. 3d. post free.

greatest possible care should be taken in storing them. It may be that a given factory does not feel justified in maintaining reference gauges for all the inspection gauges in use. It may decide to do so only in the case of certain ones, as, for example, those most frequently in use. Others can be sent periodically for checking to some central organization. The National Physical Laboratory has a routine scale of charges for the checking of gauges and measuring instruments of all descriptions.

STANDARDS OF REFERENCE

It will be clear from the principles which we have tried to outline in what has gone before that, apart from even reference gauges, there must be certain basic methods of making measurements or comparisons to the highest possible degree of accuracy. These basic methods of measurement will be the masters or standards with which the dimensions of the reference gauges may be compared. In making such measurements two fundamental standards will be required. One of these will be a standard of length and the other will be a standard of angle.

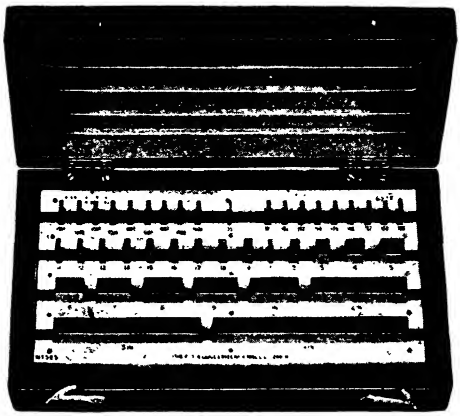


FIG. 11. SLIP GAUGES

Slip Gauges. These are rectangular steel blocks ground and lapped to the very highest order of accuracy both as regards parallelism of opposite faces and also as regards flatness. These blocks may be placed together in groups to build up any required size and their surfaces are so flat that by bringing them together with a sliding action ("wringing" as it is called) all air is excluded from the junction and they are held together by the atmospheric pressure on the opposite ends. Such gauges are supplied in sets of suitably graded sizes. (See Fig. 11.) They can be supplied in various grades of accuracy according to the purpose of use. Thus the Pitter Gauge and Precision Tool Company make three qualities as follows—*Reference* gauges are guaranteed to an accuracy of two millionths of an inch below one

inch and two millionths of an inch per inch above it. *Inspection* gauges are guaranteed to an accuracy of five millionths of an inch below one inch and five millionths of an inch per inch above it. *Workshop* gauges are guaranteed to one hundred thousandth of an inch below one inch and one hundred thousandth of an inch per inch above it.

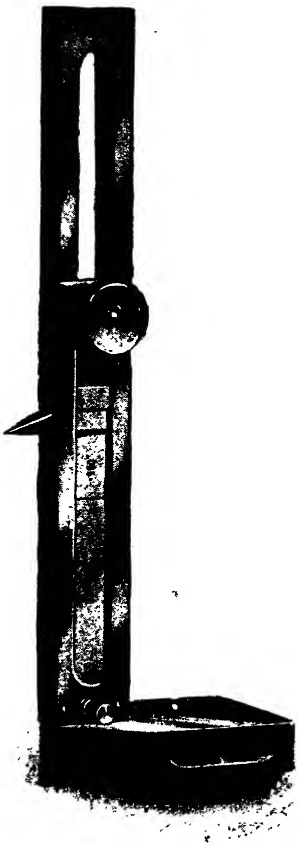


FIG. 12. HEIGHT GAUGE, USING SLIPS

In addition to the above it is possible to obtain sets of gauges made to Reference accuracy in regard to flatness but only Inspection accuracy in regard to size. These can be exactly measured by the National Physical Laboratory so that it will be known by how much they depart from nominal size and they can then be used for more exact comparisons than can the normal inspection gauges. Such sets are called Calibration sets.

Various adjuncts and accessories may be obtained for use with these gauges, as, for example, accurately made blocks and frames for building up a height gauge and scribe. (See Fig. 12.)

If required it is, of course, possible to obtain slip gauges in metric units.

Length Bars. Where it is desired to deal with lengths greater than is convenient with slip gauges use is made of length bars. These bars may be built into lengths of several feet by a process of wringing together as with slip gauges. They are produced in two standards of accuracy, namely "Reference" and "Workshop." The former are true to within 2½ parts in a million and the latter to within 5 parts in a million. As with almost all such standards the guaranteed figure applies to a temperature of 68° F.

As with slip gauges various accessories may be obtained by means of which a variety of measurements may be made, as, for example, the

distance between holes in a jig, heights greater than the compass of a normal height gauge, etc.

Roller Gauges. These may be considered as auxiliaries to slip gauges, and not alternative to them. They are specially selected rollers as used in roller bearings, and have a length equal to their diameter. They are normally supplied in sets of 16, ranging from $\frac{3}{16}$ in. to $1\frac{1}{4}$ in., and guaranteed to an accuracy of plus or minus 0·0001 in. as to both

FIG. 13. ANGLE GAUGES

length and diameter. Sets should be ordered in pairs, so as to have two of each size, in which circumstances they are extremely useful as adjuncts to slip gauges in the accurate measurement of external and internal profiles such as the angle of taper on plate gauges, etc.

Angle Gauges. Fig. 13 shows a set of gauges similar to the slip gauges already described but designed for use in the measurement of angles. They were devised by the National Physical Laboratory and are constructed by the Coventry Gauge and Tool Company. Each set contains gauges as follows—

One each 1, 3, 9, 27, and 41 degrees.
,, ,, 1, 3, 9, and 27 minutes.
,, ,, 0·1, 0·3, and 0·5 minutes.

With the above any angle may be built up (by wringing suitable gauges together) in steps of 0·1 minute.

A superior set can be supplied, if required, wherein there is an additional piece having an angle of 0·05 minute (3 seconds). (*N.B.* It will be remembered that the gauges may be wrung together in such a manner that any individual gauge either adds to or subtracts from the remainder.) In the standard set the individual pieces are guaranteed to an accuracy of 2 seconds of angle whilst those in the superior set are guaranteed to 1 second.

A useful accessory with these gauges is a small, but accurate, spirit level.

With these, as with slip gauges, a wringing contact is assisted by using a thin film of petroleum jelly. It is not advisable to use paraffin oil since this is conducive to scratches.

Absolute Standards. Whilst some firms, at any rate large ones, will consider it to be worth while to maintain, in addition to these inspection gauges, sets of reference gauges, and perhaps in addition a number of standards of reference such as slip gauges, etc., no firm would consider it worth while to keep and maintain sets of absolute standards. Such standards constitute, as it were, the highest "court of appeal." They will be made with the greatest possible skill attainable, they will be measured with instruments of the greatest accuracy which human beings can conceive, and they will be stored under conditions of the greatest possible care. Such absolute standards, whilst again not **absolutely** accurate, since it is not humanly possible to make them so, will possess the smallest conceivable errors and will be found only at such national institutions as the National Physical Laboratory and the like.

Care in Use. One of the important points to remember is that gauges are or should be correct at standard temperature, namely, 68° F. Owing to the fact of expansion or contraction with heat or cold they will not be correct at any other temperature. The coefficient of expansion of steel with temperature is about 0·000007 per degree Fahrenheit. This means, for example, that a 2 in. diameter plug with a tolerance of 0·0003 in. would be outside that tolerance for a temperature change of about 20° F. It is, therefore, important to avoid too much handling, especially with the more accurate types of gauge or instrument.

All gauges, particularly workshop gauges, are subject to wear as a result of use, and it is important to arrange for their periodical checking and to maintain records of these checks.

Co-ordination of Output. Where an article is being produced in several different departments or factories, and where it is important to ensure uniformity between these different sources of production, some definite steps towards co-ordination are necessary. This co-ordination may be carried out in various ways, but the basis is that the standards of inspection shall be uniform. To commence with, this means not merely that the same specification and test sheets should be used by the inspectors at the different factories, but that the inspectors themselves should place a common interpretation upon the specification. We have heard of too many cases where articles which have passed one inspector have been rejected by another who is inspecting a major assembly of which the article constitutes a component. This can happen only where there is a looseness of organization amongst the inspection staff.

Having ensured that the inspectors themselves are uniform in their ideas, the next thing is to ensure uniformity of gauges, etc. This can be done in various ways. One method is to arrange that all articles are sent to one central depot for inspection. Often, however, considerations of time, transport delay, etc., prohibit this. In such cases it is possible to arrange that inspection gauges, etc., from the various factories shall be sent to a central depot to be checked periodically against a "master" or "sub-standard" set of gauges. Sometimes, owing possibly to the delicacy of the gauges or instruments, this is not suitable or advisable and it may then be worth while sending a certain percentage of the output of each factory to one or another of the other factories for re-check by the inspection staff there. This will show whether articles which have passed or been rejected at one place pass or are rejected at another and so, by implication, will form a guide as to uniformity of inspection.

CHAPTER VI

VARIOUS GENERAL PURPOSE MEASURING INSTRUMENTS

THE VERNIER

We have said that the human eye can perceive a coincidence between two marks far more easily than it can estimate a proportion of a subdivision represented by a mark lying between two others at a known distance apart.

Thus Fig. 14 (*a*) shows a mark *M* at a distance which lies between

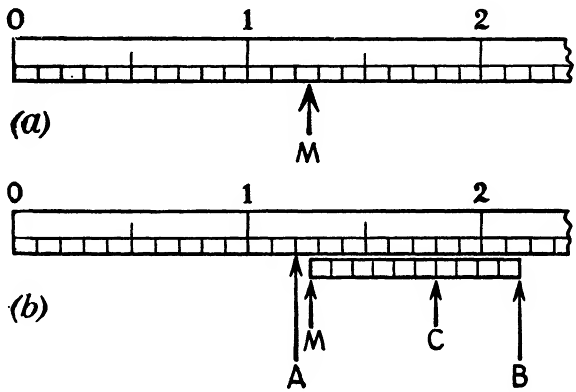


FIG. 14. VERNIER PRINCIPLE

1·2 and 1·3, but it is difficult to estimate very closely between the two. In Fig. 14 (*b*) the single mark is replaced with a short length of scale of which the point *M* constitutes the datum mark. The total length of this short scale is equal to nine divisions of the main scale, but it is divided into ten equal parts. Thus each division of this scale, which is called the Vernier, is equal to 0·09, whereas each division of the main scale is equal to 0·1.

Thus the difference between the length of a main scale division and the length of a Vernier division is 0·01. If now we look along the Vernier we shall find that one—and only one—of the graduations coincides with a graduation of the main scale. In Fig. 14 (*b*) we see that it is the sixth graduation. Working backwards, therefore, we see that the distance between *C* and *M* is less than the distance between the corresponding number of *main* graduations by (in the particular case shown)

six times 0·01, i.e. 0·06. But this difference is clearly the distance between M and A. The reading of the point M is 1·2 plus the distance AM, which we see is in this case 0·06, so that one reading is 1·26. In general, therefore, if it had been the nth graduation of the Vernier which corresponded with a main graduation the reading would have been 1·2 plus n times 0·01. Such a type of Vernier is known as a "Hundredth" Vernier.

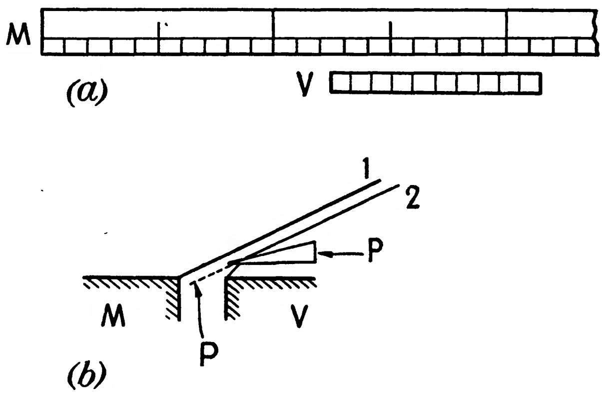


FIG. 15. SCALE VIEWING PRISM

Sixty-fourth Vernier. In many cases it is convenient that the reading should be in inches and sixty-fourths (or multiples thereof) of an inch. In these cases the main scale is divided into inches and eighths, whilst the Vernier is seven-eighths long and divided into eight parts. It follows that the difference between a main division and a Vernier division is one sixty-fourth of an inch, so that the "extra bit" to be read by the Vernier is the number of Vernier scale divisions to the point of coincidence multiplied by one sixty-fourth of an inch.

Thousandth Vernier. Where it is required to read to the third place of decimals each main scale unit is divided into 40 parts (instead of ten as in Fig. 14). In this case the length of the Vernier is equal to 24 of these fortieths, and is divided into 25 equal parts. Thus each subdivision of the Vernier is less than a subdivision of the main scale by $\frac{1}{40}$ minus $\frac{1}{40} \times \frac{24}{25}$, which is 0·001. It is pointed out that, with this Vernier, coincidence is more easily detected by aid of a small-power magnifying glass.

Vernier Reading Prism. It frequently happens that the distance between the mark or Vernier and the main scale is, or has become, somewhat large so as to make the accurate estimating of a coincidence

very difficult, as shown in Fig. 15 (*a*). In these cases an ingenious device due to Messrs. Bellingham & Stanley is of great value. In Fig. 15 (*b*) the main scale *M* and Vernier *V* are shown from a side view. A narrow angle prism *P* is carried over the Vernier. The lines 1 and 2 represent rays of light coming respectively from the edges of the main scale and the Vernier. It will be seen that ray 2 **appears** to come from the direction of the broken line *P* (continuation of ray 2) or, in other words, the Vernier appears to be closer to the main scale.

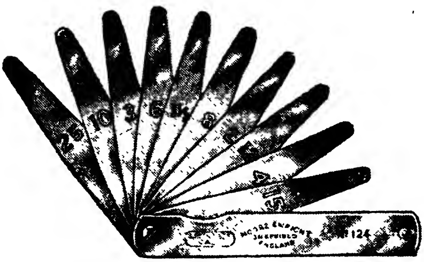


FIG. 16. FEELER GAUGES

Feeler Gauges. These are thin slips of stainless steel ground to exact thickness within close limits. They are usually supplied in sets of various thicknesses, according to requirements, as shown in Fig. 16. With a suitable set any gap thickness may be tested by, if necessary, using two or more blades together. In using feeler gauges the accuracy with which it is possible to test a gap depends to a large extent upon the area of the opposite faces of the gap. Whereas a skilled worker can estimate to a fairly close accuracy, the touch of an unskilled worker may be so inexperienced as not to be able to judge more closely than as much as 0·0005 in. (half a "thou.").

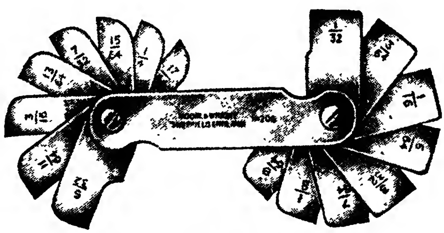


FIG. 17. RADIUS GAUGES

Radius Gauges. Fig. 17 shows a set of these gauges which may be obtained in a variety of ranges. Their use is self-evident.

Engineers' Squares. The ordinary hardened try-square as shown in Fig. 18 may be obtained in a variety of sizes. The usual accuracy is of the order of 0·0005 in. to 0·001 in. "out of square" per foot length of blade measured at the extremity of the blade.

Messrs. Moore & Wright (Sheffield) have produced a more accurate and stable square which is illustrated in Fig. 19. These squares are made to what is known as N.P.L. grade A standard. Their limits for squareness range from 0·0001 in. for the 3 in. blade size through 0·0002 in. for the 12 in. blade size to 0·0003 in. for the 24 in. blade

size. Their rigidity is such that, with the stock vertical, the blade of the 24 in. size does not deflect by its own weight more than 0·0002 in. at its extremity.

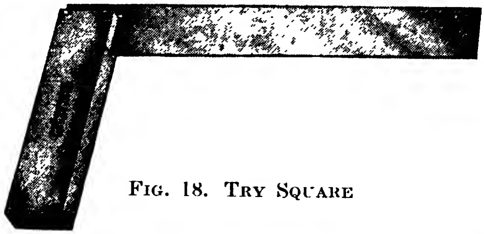


Fig. 18. Try Square

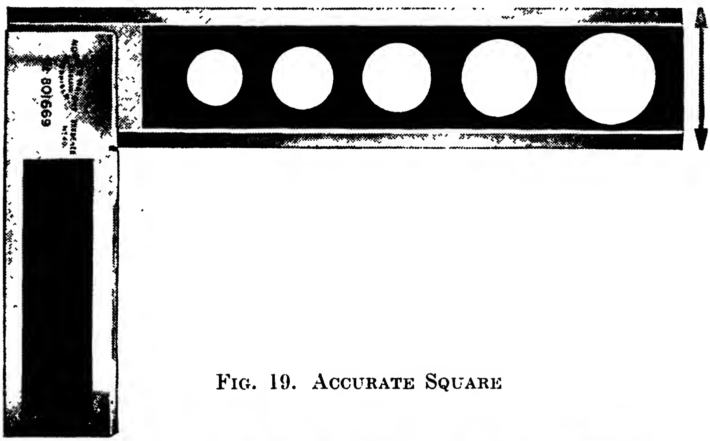


Fig. 19. Accurate Square

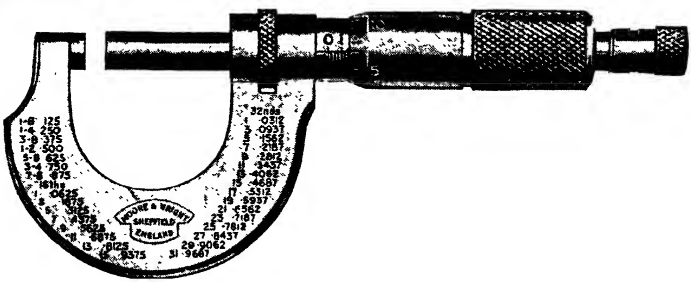


Fig. 20. Micrometer Callipers

Micrometer Callipers. Fig. 20 shows a typical form of one of these instruments, which may be obtained in a variety of sizes and shapes. The principle is that the gap is varied by rotating the "thimble," which causes a nut to draw along itself a lead screw. The small

extension to the thimble (at the extreme right of the illustration) drives the thimble through a ratchet so that undue pressure cannot be exerted when the jaws close on the work. (This ratchet device is very desirable but is not universal.) The pitch of the lead screw is very accurate along its length, and the movement is read partly by graduations along the inner sleeve over which the thimble slides, and partly by means of graduations round the edge of the thimble.

Thus, suppose the screw to have 20 threads per inch, each revolution of the thimble will uncover (or cover up) another graduation on the inner sleeve $\frac{1}{40}$ in. from the previous one. Since $\frac{1}{40}$ in. is equal to $\frac{25}{1000}$, it is clear that if the thimble be graduated with 25 equal divisions around its edge the space between any two of these divisions represents a movement of the lead screw equal to $\frac{1}{25}$ times $\frac{1}{40}$, which is equal to $\frac{1}{1000}$ of an inch. We thus have a means of reading to the nearest $\frac{1}{1000}$ in. Since, however, it is possible to "estimate" between graduations on the sleeve it is possible to read to a few "ten thous."

By providing a Vernier on the sleeve for reading the last decimal point it is possible to make such a micrometer read to $\frac{1}{10000}$ in. The limits of accuracy laid down by the British Standards Institution for high-grade external micrometers are given in Table II (only three sizes shown).

TABLE II

B.S.I. LIMITS FOR EXTERNAL MICROMETERS READING TO 0·001 IN. (0·0001 IN. BY VERNIER)

Maximum Permissible Errors

Range of Micrometer Inches	Anvil Faces		Zero Inches	Screw Pitch Inches
	Flatness Inches	Parallelism Inches		
0–1	0·00005	0·0001	± 0·00005	0·0001
5–6	0·00005	0·0002	± 0·0001	0·0001
11–12	0·0001	0·0003	± 0·0002	0·0001

The flatness of micrometer anvils may be conveniently tested by means of optical flats. (See page 83.)

Micrometers may be obtained with specially shaped anvils for such particular purposes as the measuring of screw threads or the measuring of soft materials such as paper, etc. They may also be obtained with specially shaped frames for dealing with awkward

conditions, such as the measurement of the thickness of the wall of a hollow container and a variety of other purposes.

A very useful tool in any inspection department is a Bench Micrometer. This instrument is usually mounted upon a base and should possess a large (about 2 in.) diameter thimble from which it is possible to make direct readings in $\frac{1}{10000}$ in.

Fig. 21 shows a form of expanding micrometer. The principle is the

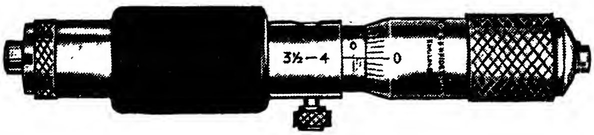


FIG. 21. INTERNAL MICROMETER

same as the foregoing, but it is used for measuring **internal** distances such as, for example, that between the faces of a gap.

Combination Sets. A typical set is illustrated in Fig. 22 and comprises what are known as Centre Head, Protractor Head, and Square

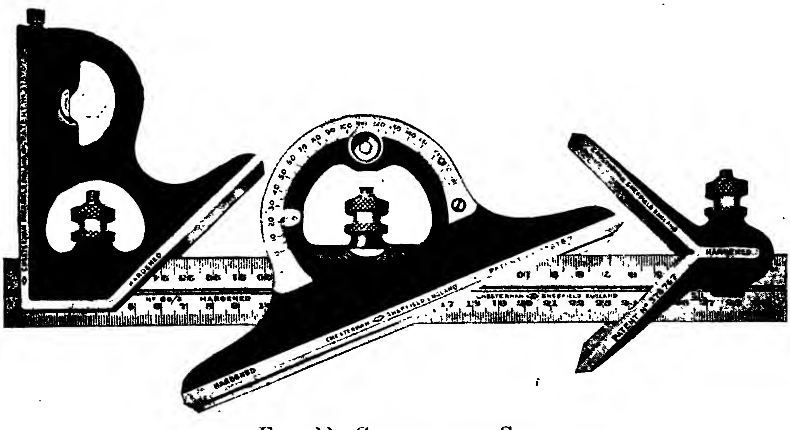


FIG. 22. COMBINATION SET

Head. These are mounted in such a manner that they may be removed from or mounted in any position on an engraved steel rule. These sets are capable of being used for many purposes which do not need to be described in detail.

Dial Indicators. Fig. 23 shows the typical form of such gauges. That illustrated is one made by Messrs. J. E. Baty & Co. They may be obtained in a variety of sizes and in types, the graduations of which

are separated by 0·0001 in., 0·0005 in., or 0·001 in. (Other types may also be obtained, but these are most usual). They are very delicate mechanical multipliers, and will give reasonably satisfactory service over long periods if carefully used. Since the majority of such dials depend for their movement upon racks and pinions their accuracy over long ranges is not, in general, so great as is that of micrometers. Their best type of use is where comparisons have to be made and where the variations over any given set of readings do not differ by more than a few divisions. If it is desired to use the entire range of the indicator (especially if it is to be over several revolutions of the large hand) it is usually necessary to calibrate it against slip gauges.

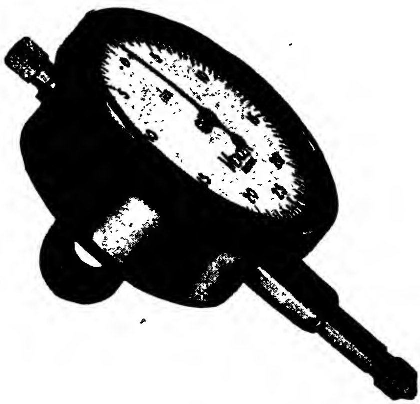


FIG. 23. DIAL INDICATOR

In selecting a dial indicator it is important to ensure that the force required to depress the plunger is not too great, that the movement is not harsh and "lumpy" when the plunger is depressed by hand, that indication is made of small movements (e.g. a few "ten thous."), and that lateral movement of the plunger does not affect the reading, which, if such were the case, would be different for work passed forwards from that passed backwards under the plunger. Similar differences might be noted as between right to left and left to right.

When an indicator is used on a stand it is important that the rigidity of the stand should be high compared with the force required to depress the plunger. This is by no means always the case.

Comparators, Vertical. These instruments are intended for making a comparison between the dimensions of two articles very nearly alike. They do not make direct measurement. Fig. 24 shows a simple but robust type of instrument made by the Newall Engineering Company.

It employs a dial (or "clock") indicator and is intended for making rapid examinations of either rectangular or cylindrical work. Slip gauges are first wrung together to the required "plan" dimension and placed upon the table beneath the dial indicator plunger. The table is then raised until the top of the set of slip gauges depresses the

plunger so as to give a definite reading on the clock. The slips are then removed and the "work" substituted for them. The difference in the dial reading is a measure of the error in the dimension. Such an instrument, once it has been set up, can be used by semi-skilled operators for the rapid inspection of a number of similar articles. The permissible limits may, if thought advisable, be marked on the glass of the clock face by the operator setting it up.

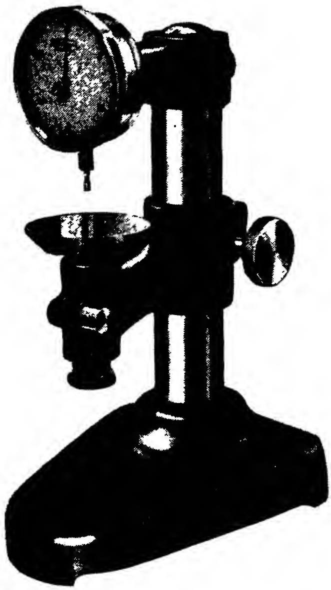


FIG. 24. DIAL COMPARATOR

A more elaborate, and much more accurate instrument of this type is one shown in Fig. 25. This is made by Optical Measuring Tools, Ltd. It goes under their trade name of the Vertical Omtimeter. The dial is replaced by an image pointer moving over a vertical illuminated scale. The movement of the plunger rocks a small mirror, which thereby swings a beam of light. Readings of 0·00001 in. may be estimated when viewed through the eye-piece or when projected on to a screen in an attachment which can be provided with the instrument. To be consistent with such sensitivity the table is "worked" so as to be optically flat, and may be adjusted so as to be truly parallel to flat or knife-edge contact tips on the plunger. Under such conditions these types of tips are, from many points of view, to be preferred to the more usual spherical tip, which, however, is preferable when such table refinements are not available.

Comparators, Horizontal. These instruments are, in general, much more elaborate than those of the vertical type, and may be supplied with various attachments, by means of which a very wide range of accurate comparisons may be made.

Fig. 26 shows the main parts of such an instrument manufactured by Messrs. Cooke, Troughton & Simms. In essence a comparison is made between the work and a standard as measured between the tailstock (which may be withdrawn by the knob 3) and the recording plunger which, through a simple lever and mirror mechanism, causes a magnified image of an illuminated scale to be moved in relation to a fixed

index. The work is carried on the table 15, which is capable of being raised by hand wheel 9 or tilted by hand wheel 13. Various types of

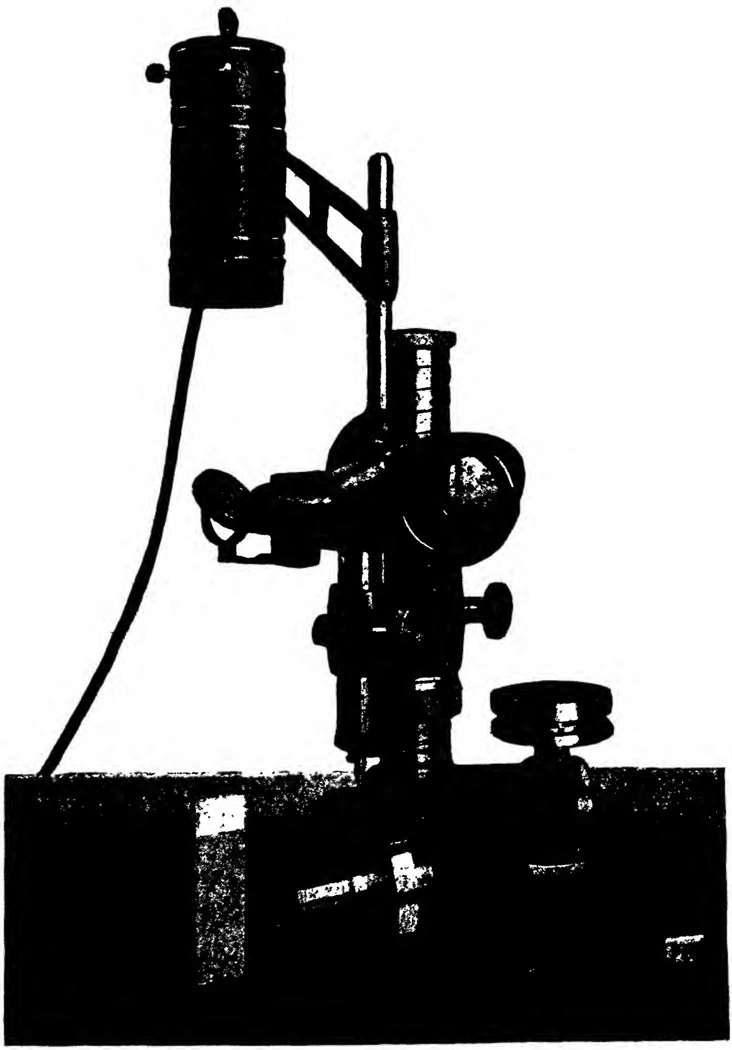


FIG. 25. VERTICAL COMPARATOR

table and table attachments are available according to the work requiring to be examined.

Since it is important that the axis of measurement is square with

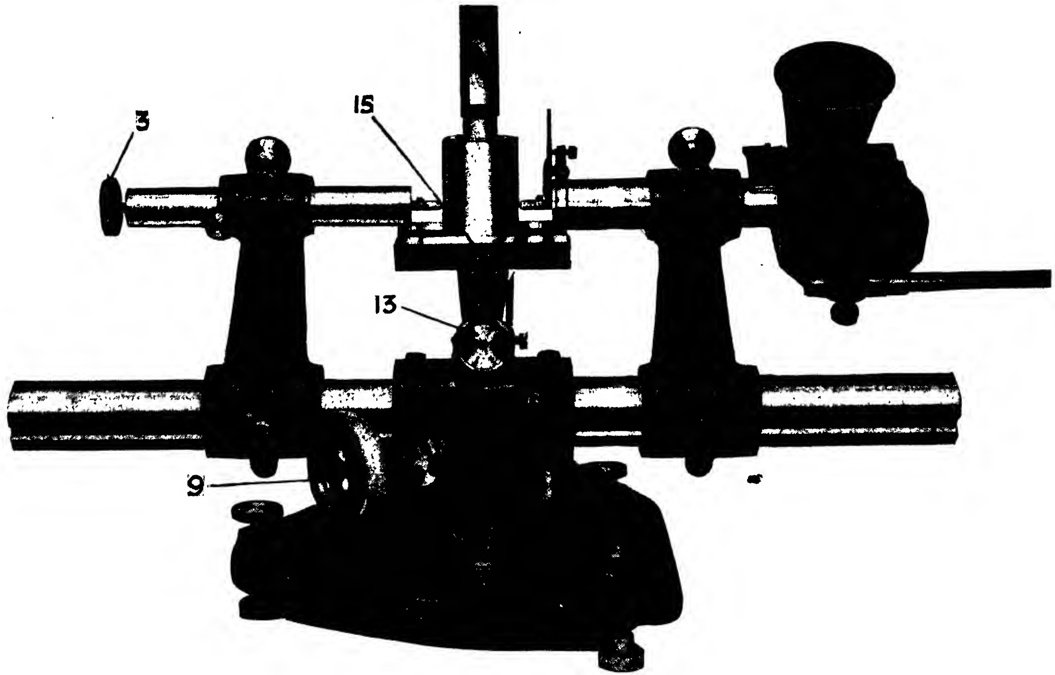


Fig. 26. Horizontal Comparator

the end faces, the various table adjustments, including, if necessary, one of rotation, are essential. Fortunately it is a relatively simple matter to make these adjustments by the aid of the optical indicator itself, since, as the adjustment passes through its optimum position, there is a reversal in the direction in which the reading changes.

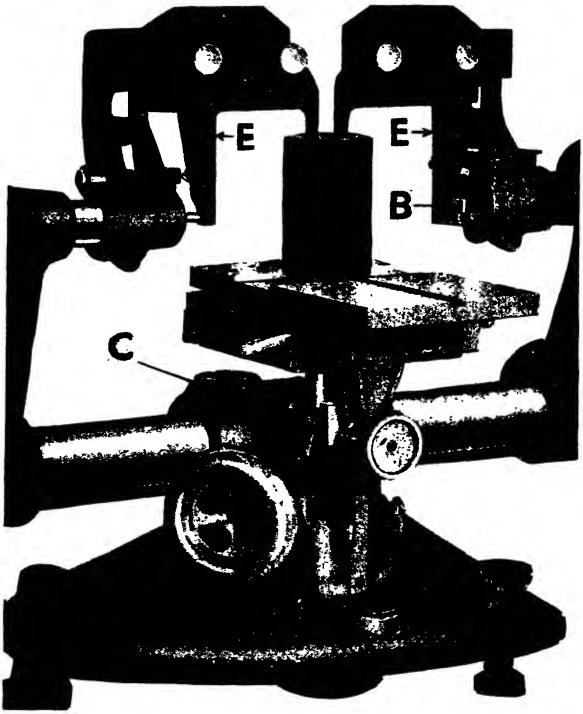


Fig. 27. Horizontal Comparator Attachments

Fig. 27 shows a pair of attachments for use when internal dimensions are under consideration. Other types of comparison which may be made are—

Verification of diameter and roundness of plug gauges.

Verification of diameter and roundness of ring gauges.

Verification of all dimensions of taper plug gauges.

Verification of all dimensions of taper ring gauges.

Verification of thread plug gauges, using either special tips or else by three-needle system.

Verification of thread ring gauges.

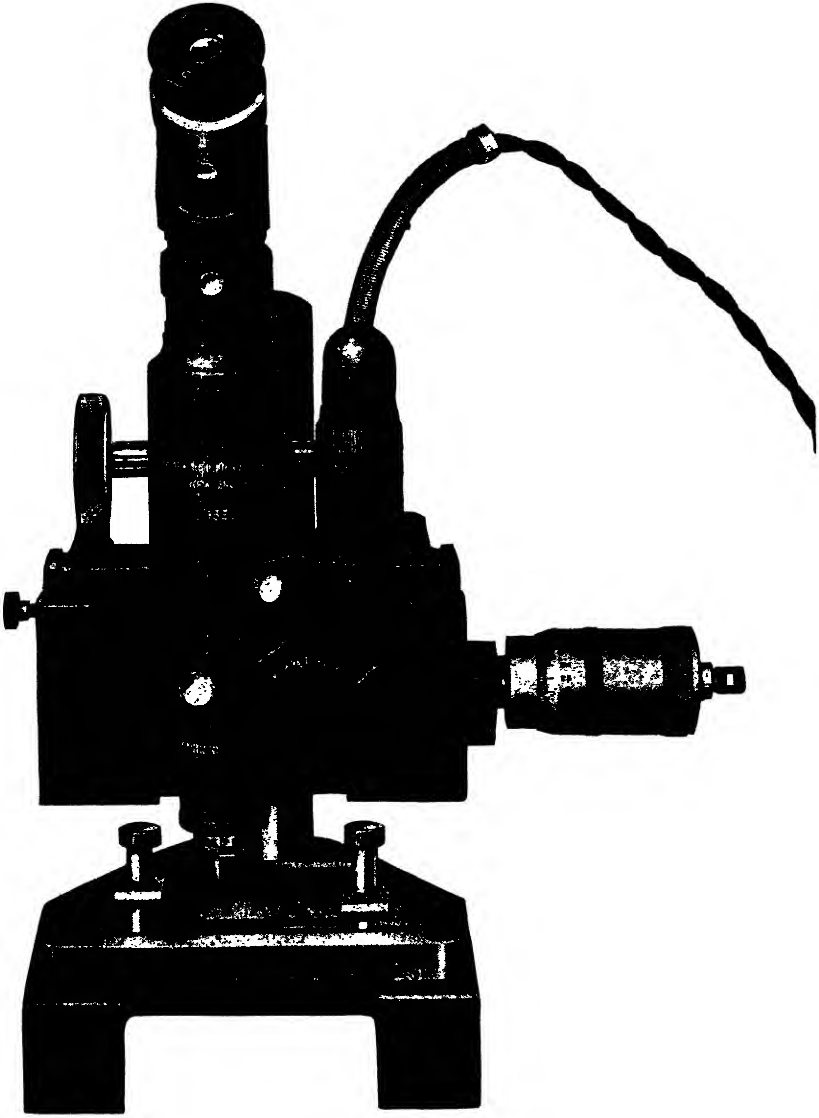


FIG. 28. WORKS MICROSCOPE

In all cases it is implicit that the requisite slip gauges are available for the initial setting up.

Works Microscope. An instrument of this type produced by Messrs. Cooke, Troughton & Simms is illustrated in Fig. 28. It can be supplied

with either straight or inclined eye-piece and magnifications of 40, 24, or 15 are obtainable with the former, whilst 64, 40, or 27 are obtainable with the latter.

The microscope is mounted on a ball-bearing slide with a range of traverse of 1 in. under the action of a micrometer head each division of which corresponds to 0·0002 in.

A circular measuring stage can be mounted on the plain stage.

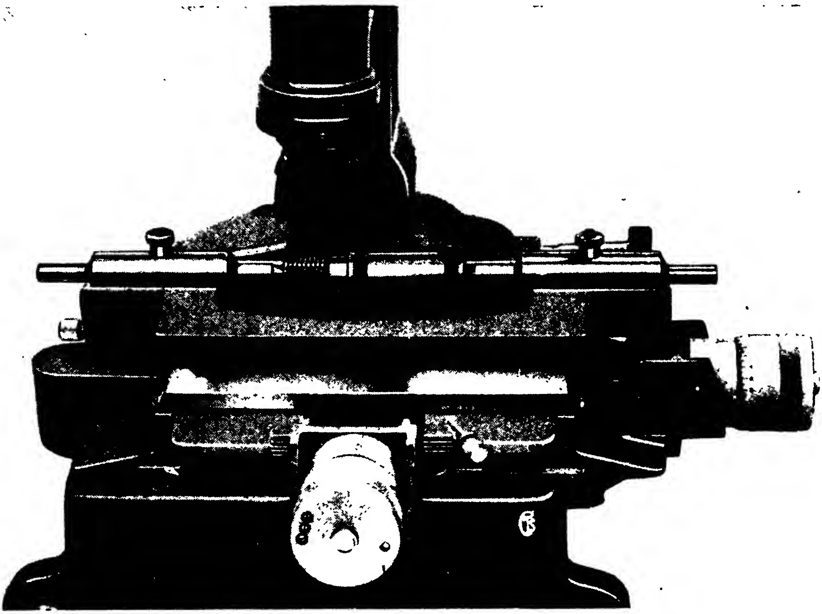


FIG. 29. TOOLROOM MICROSCOPE

Toolmaker's Microscope. This type of instrument is, in a sense, an elaborate edition of the works microscope. In this case, however, as will be seen in Fig. 29, it is the work, and not the microscope, which is moved. Total longitudinal movements of 4 in. and lateral movements of 2 in. are obtainable by means of the two micrometer screws, in which each division represents 0·0001 in. The total scope of the micrometer movement is only 1 in., but this can be extended by means of suitable slip gauges for the insertion of which provision is made.

In addition to an eye-piece, there is a projection screen on which profiles of, for example, thread or gear forms may be inspected.

A protractor unit can be mounted on the body tube of the microscope. It carries a glass disc whose circumference is graduated in degrees, which graduations are observed through an auxiliary eye-piece. This auxiliary eye-piece carries a reticule of 60 lines, which exactly span one degree, so that the protractor scale has, in effect, divisions of 1 minute.

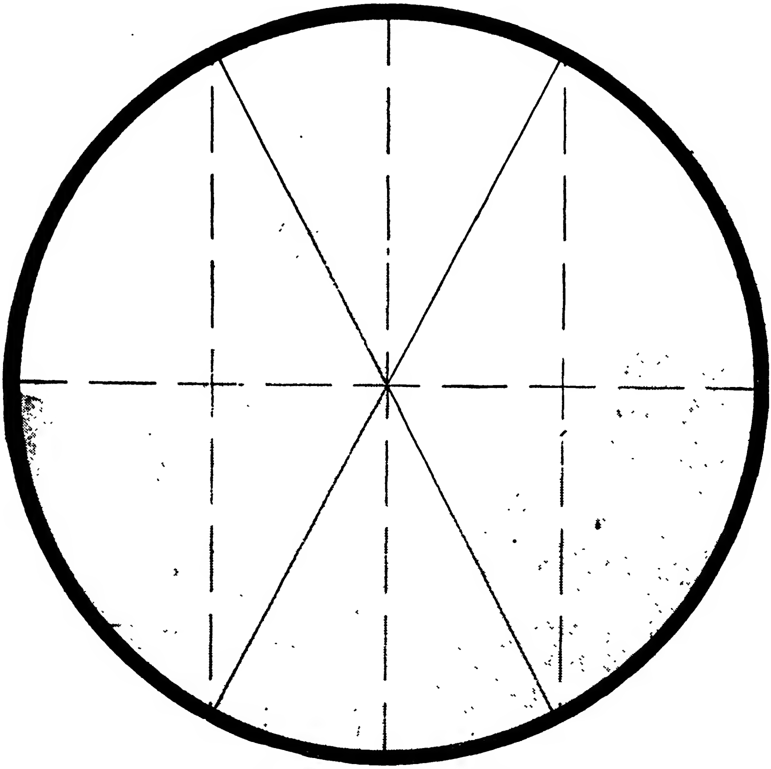


FIG. 30. PROTRACTOR UNIT

Coincident with the centre of the protractor are fiducial lines which serve as index lines for setting to the parts to be measured, as shown in Fig. 30.

A further item is a thread form attachment for mounting in the focal plane of the eye-piece. This is rotatable so that any particular thread form may be brought into the field of view in order that the work under test may be compared with it.

Contour Projector. This type of instrument is used for throwing

on to a screen a magnified image of an object, such as a worm or gear tooth, in order that it may be compared with a drawing or tracing made accurately to the necessary degree of magnification.

Fig. 31 shows a typical example of this type of instrument and, as we have already stated in Chapter III, it is in the highest degree

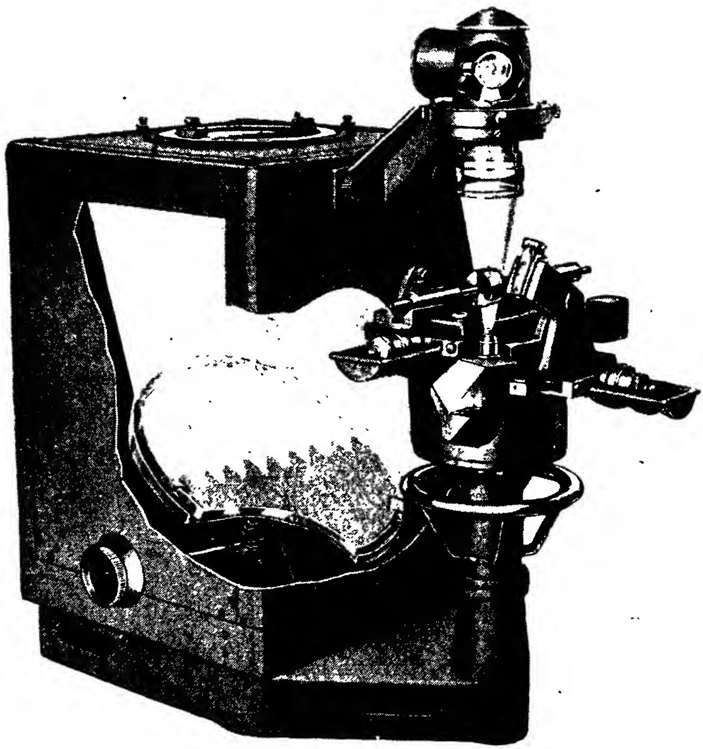


FIG. 31. OPTICAL PROJECTOR

important that the optical system should give true magnification over all the field of view. The one shown is highly accurate and is manufactured by Messrs. Cooke, Troughton & Simms.

Fig. 32 shows a close view of the circular stage arranged for the examination of plane objects.

Optical Dividing Head. Although perhaps strictly speaking this is an adjunct rather of the tool room than of the inspection department,

yet its functional uses are so great that it must be included amongst our descriptions.

Fig. 33 shows a typical dividing head proper. This may be mounted on a suitable base plate in conjunction with a tailstock.

Although, as will be seen on the right of the picture, the head is

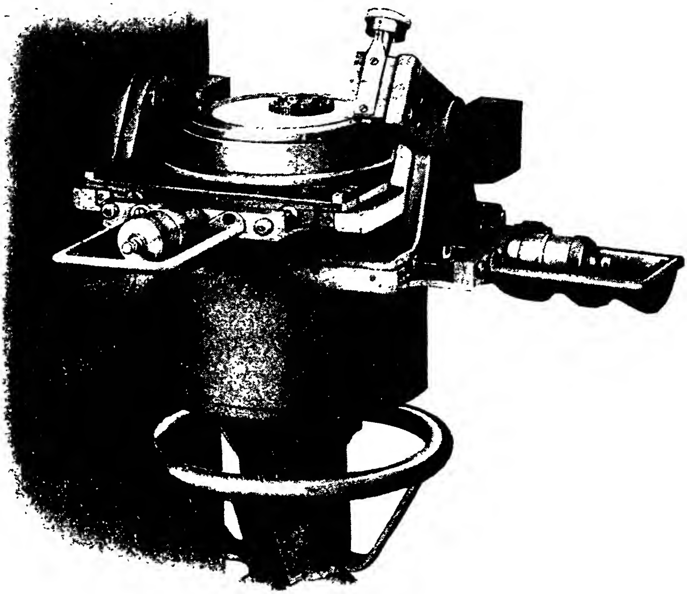


FIG. 32. PROJECTOR STAGE (ENLARGED)

provided with a scale marked in degrees, this is of use only for coarse measurements. The interior of the head is fitted with a graduated glass circle. (These circles can now be produced to a very high degree of accuracy.) The divisions of the circle are at every 20 minutes, and an optical micrometer, associated with the eye-piece providing the necessary magnification of view, permits each 20-minute interval to be subdivided into divisions of 0·5 minute. The accuracy of measurement is of the order of 10 seconds of arc.

As will be seen in the illustration, it is possible to elevate the head on a horizontal axis, which permits a very wide range of inclined work. An elevation scale and Vernier are fitted, but for very accurate work it is desirable to use an optical clinometer as shown.

This clinometer is fitted with a sensitive spirit level (30 seconds per

2 millimetre run) and, when set, the angle of elevation is read by means of an eye-piece off an internal glass scale, as with the dividing head.

Jig Borer. As with the optical dividing head, this machine is found rather in the tool room than in the inspection department.

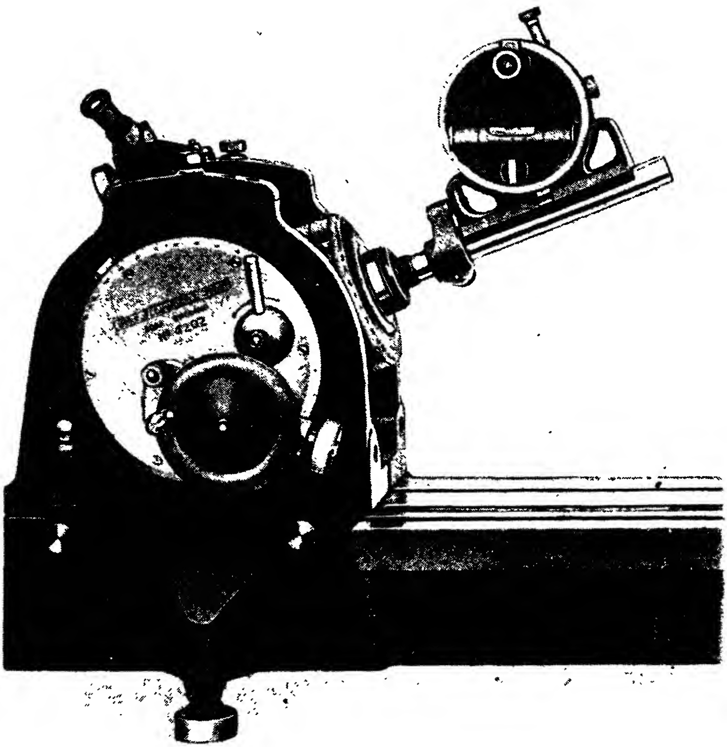


FIG. 33. OPTICAL DIVIDING HEAD

In essence the machine is one with a vertical boring spindle and with a table whose movements may be set to a very high degree of accuracy, viz. of the order of 0·0002 in.

Fig. 34 illustrates one of these machines manufactured by the Newall Engineering Company, Ltd. Longitudinal and cross movement of the table are measured in the following way. Associated with each there is a train of accurately ground rollers parallel to and touching one another. These rollers are ground to an accuracy of plus or minus 0·00002 in., and their nominal diameter is 1 in. Associated with these

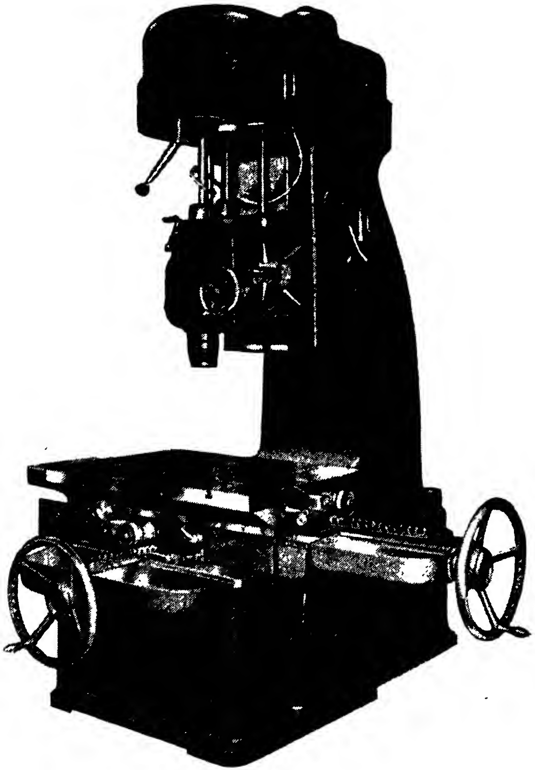


Fig. 34. Jig Borer

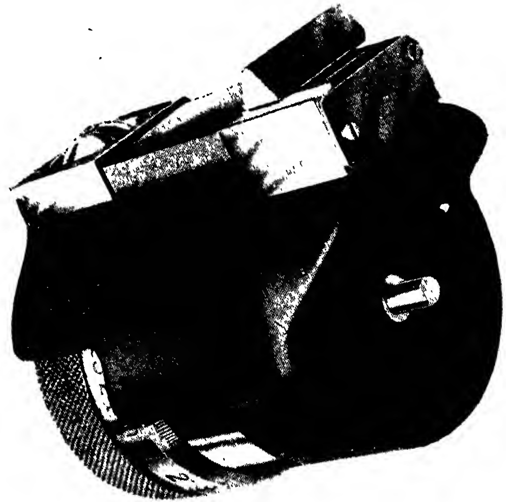


Fig. 35. Jig Borer Locator

is a micrometer locator. (See Fig. 35.) This may be set in steps of 1 in. by resting the knife edge between any pair of rollers. Further adjustment is obtained by the micrometer head. A dial indicator is fitted in addition, but merely to duplicate the "fine" readings. Fig. 36 shows the micrometer locator in position.

A useful accessory to such a machine is a rotary inclinable table, an example of which, manufactured by Optical Measuring Tools, Ltd.,

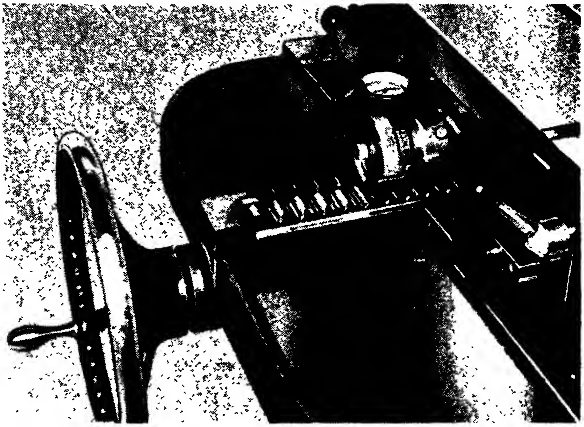


FIG. 36. JIG BORER LOCATOR IN USE

is shown in Fig. 37. Readings of both rotation and tilt are taken on optical divided circles and may be estimated to about 6 seconds of arc.

Fiducial Stops. Many inspection operations demand that the work shall be set against a stop supposedly fixed. Where, however, very great accuracy indeed is required the elasticity or lack of rigidity of the stop may be such a variable quantity that reliance cannot be placed upon it for exactly positioning the work. The difficulty is sometimes overcome by arranging that the work is always held against the stop by means of a constant pressure. In other cases the stop is such that its slightest movement may be recorded. This may be done by employing a sensitive dial gauge.

Another method of indicating movement of the stop is to employ a delicately pivoted spirit level which is tilted by a sensitive lever mechanism from the stop. Sometimes the level of a fluid in a narrow bore tube is used as the indicator. The level is controlled by a diaphragm against which the stop bears.

Some instruments incorporate a fiducial stop of such a type, and Figs. 53, 81, and 113 are examples of such.

It is often convenient to be able to use a stop which is retractable but which, at the same time, is fiducial. In the testing of a gear wheel, for example, it may be required to rotate the wheel tooth by tooth through exactly the tooth pitch angle. In this case the stop is withdrawn, the wheel rotated through approximately the pitch angle, the

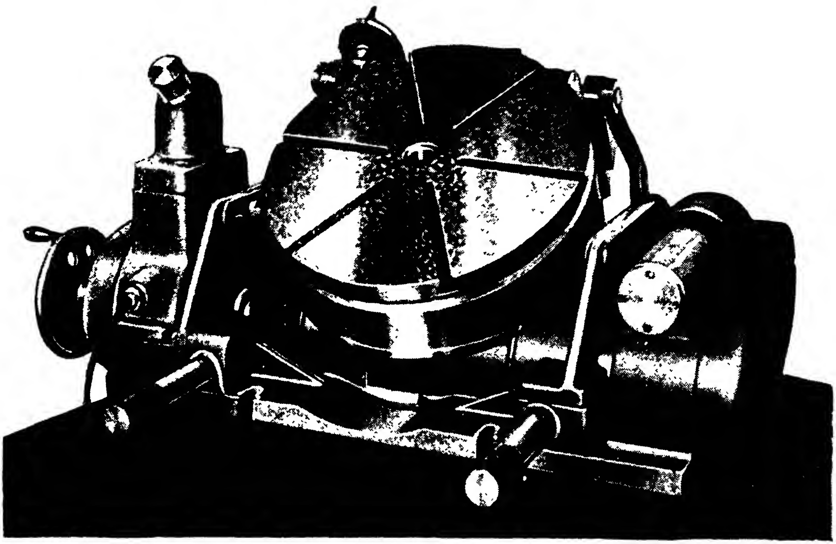


FIG. 37. ROTATABLE INCLINABLE TABLE

stop returned to its position, and the wheel once more exactly set to the stop.

An instrument of this type, based upon the design developed by the late Dr. Tomlinson of the Metrology Division of the National Physical Laboratory, has been made by and is employed in the department of Chief Inspector of Armaments. It is illustrated in Figs. 38 to 41.

Fig. 38 shows the complete arrangement, which, in fact, comprises two retractable stops, one on each side of the gear wheel under examination. At the forward end of the shaft there is a sine bar attachment, the principle of which is described in Chapter IX.

Each stop unit comprises a heavy cast-iron housing in which is supported the retractable stop proper. This latter is shown in Fig. 39. To its base are fixed two leaf springs of phosphor bronze (shown at

EE) which have stiffening plates along the major portion of their length. At their upper ends *DD* these springs are firmly fixed to the main housing. This arrangement permits "fore and aft" movement without lateral movement or twist. The hardened surface *S* bears against a hardened stop on the main housing under the action of two spiral springs (not shown) fixed to the ends of the two horns *H*. In the closed position, therefore, the location of the stop in the fore and

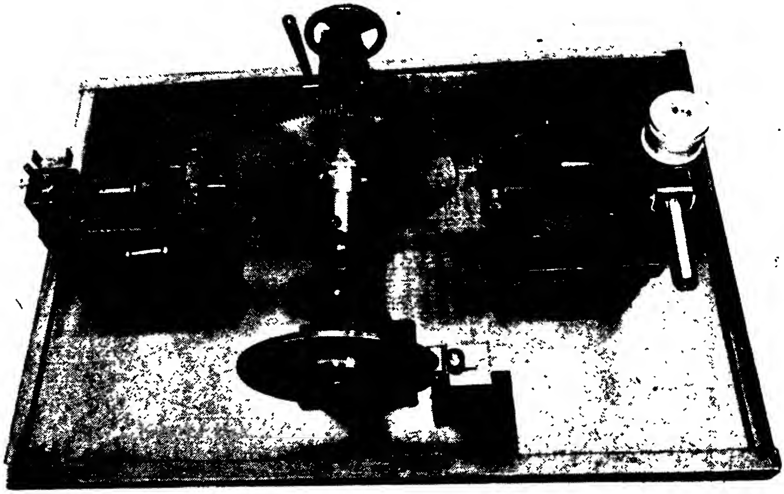


FIG. 38. RETRACTABLE STOPS

aft direction is definite. Withdrawal takes place under the action of the mechanism *L*.

The contact stylus *A* is carried at the end of a lever arrangement fixed to the main retractable unit by the plate *B*. The lever is hinged to *B* by the crossed springs shown at *SS* in Fig. 40. This provides a definite axis of "hinge" whilst not being subject to errors due to wear.

The tail *C* of the contact stylus lever locates by means of a fiducial stop carried on the main housing. The unit on the left of Fig. 38 has a simple fiducial stop with an anvil end so that, when in position, the stylus *A* is exactly located both in the fore and aft direction and also in the vertical direction. The movement of *A* is very greatly multiplied at *C*, so that great accuracy of setting is possible. A simple device (not shown) permits a slight but constant bias to be applied in either

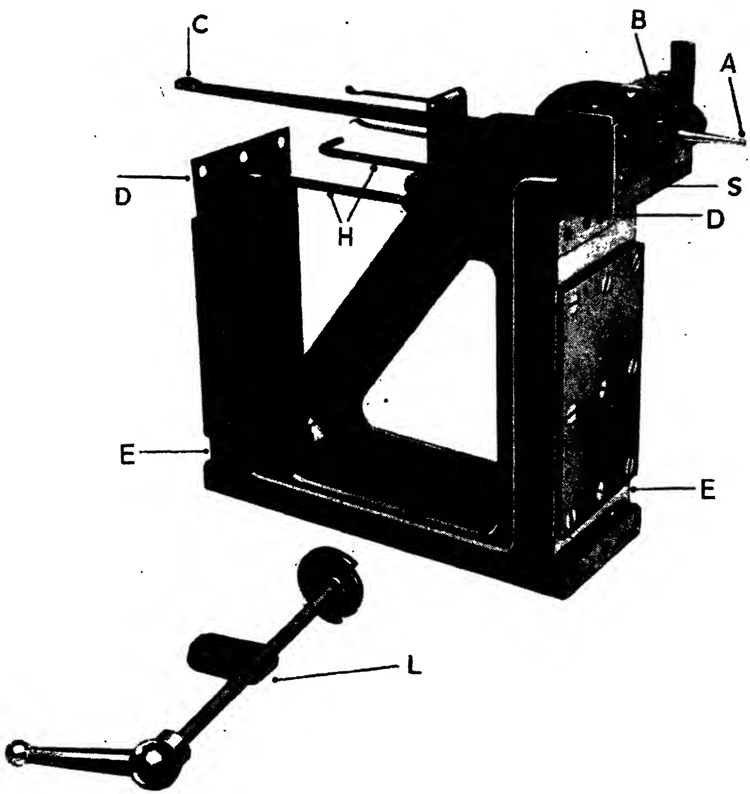


FIG. 39. RETRACTABLE STOP MECHANISM

FIG. 40. RETRACTABLE STOP, STYLUS

the upwards or the downwards direction to the stylus lever, so that *A* may be brought to bear on either the lower or the upper side of a tooth as desired.

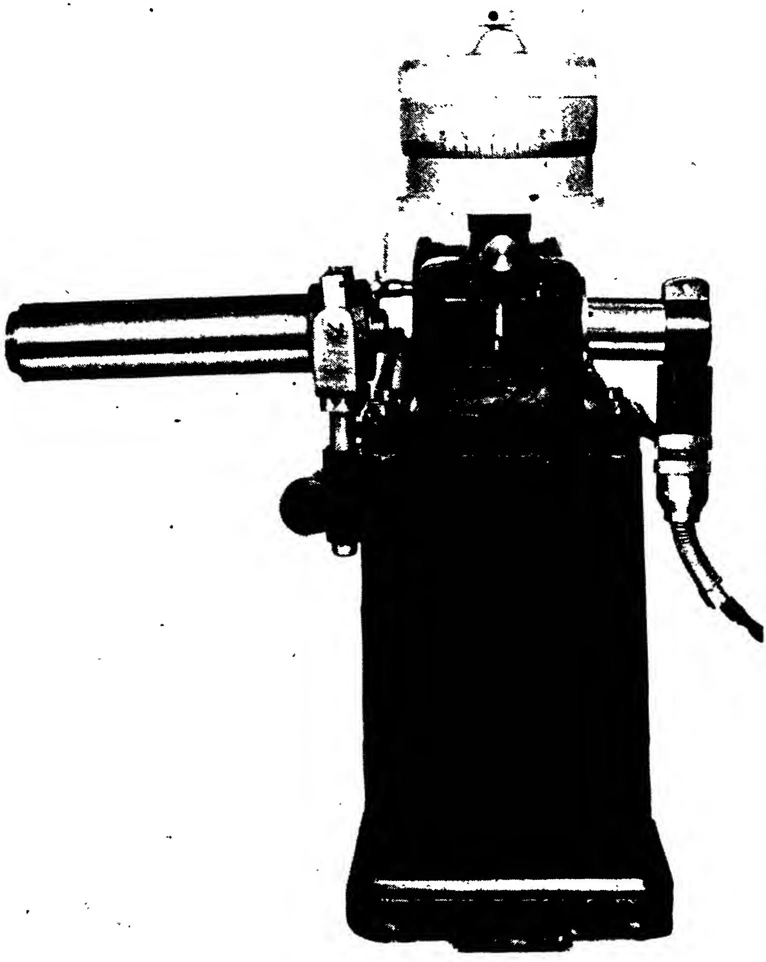


FIG. 41. RETRACTABLE STOP, TELESCOPE

The unit shown on the right of Fig. 38 has, in place of a fiducial stop, an accurate micrometer so that, when the gear under test has been exactly located rotationally by means of the left-hand unit, departures from normal may be read by means of the micrometer head, since it

is a simple matter to set its anvil to the point of just touching the end C of the stylus lever. In order to facilitate this operation the main housing carries a lamp and viewing telescope, as shown in Fig. 41. The sine bar arrangement permits readings of definite amount of angular rotation to be made.

Optical Collimators. These optical devices are used normally in conjunction with the measurement of angles. They have many optical applications beyond the purpose of this book, as, for example, in ensuring the coincidence of the optical and mechanical axes of telescopes,

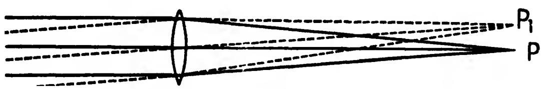


FIG. 42. COLLIMATOR PRINCIPLE

or the parallelism of the two portions of a pair of binoculars. In addition to such uses they are frequently employed for determining or comparing mechanical angular movements.

A collimator consists essentially of a tube in which is mounted, at one end, an illuminated graticule and, at the other end, a lens set so that the image of the graticule is at infinity. If now this image is viewed through a telescope set to infinity, the illuminated graticule will be brought into focus. The arrangement, therefore, behaves as though we were employing a mark at an infinite distance; but it possesses the advantage that it may be used in a small space and is independent of the weather. The advantage is still greater when it is desired to employ several collimators whose axes are at given angles to one another since the employment of distant marks for the same purpose requires a good deal of room and is very dependent upon weather conditions, visibility, etc., in use.

Fig. 42 shows diagrammatically the path of rays of light through such a collimator. The full lines proceeding from the point P, on the optical axis, emerge in a beam parallel to the optical axis. The broken lines, proceeding from the point P_1, emerge in a parallel beam, making an angle with the axis depending upon the distance between P and P_1 and also upon the focal length of the lens. It is thus possible to use as our graticule, instead of a single point, a small scale whose subdivisions represent angles of departure from the optical axis. The viewing telescope will be fitted with some form of graticule which may, for the sake of clarity, be supposed to consist of a single line. This line will coincide with the image of some such point as P_1 when the telescope

axis is parallel to the emergent beam of rays corresponding to that point. It is clear that there is no advantage in employing in the collimator a total scale representing a greater angle than can be picked up by the object glass of the viewing telescope.

It is sometimes convenient to fit the viewing telescope with a scaled graticule instead of, or in addition to, that in the collimator. In this case the actual size of the divisions for a given angle will, as with the collimator, depend upon the focal length of the system employed in the telescope.

We saw in Chapter III that there are various sources of error which can occur in optical systems. Dependent, therefore, upon the degree of accuracy desired, it will be necessary to ensure the correctness of the optical system employed. If, for example, the beam of rays emerging from the collimator is not a parallel one, the angle from which they will *appear* to come will depend upon the portion of the beam in which we place our viewing telescope. Such departure from parallelism can occur for various reasons connected with the impurity or otherwise of the lens system. It will, however, also occur if the diaphragm is not placed exactly in the focal plane of the collimator. It is, therefore, important to see that this is accurately done. Providing that the lens systems in collimator and telescope are reasonably pure, no large error is introduced, even though the axis of the viewing telescope is slightly "off" that of the collimator.

Although, theoretically, there is no limit to the amount of subdivision which is possible in a graticule scale there are practical limits to manufacture and also to the extent to which magnification is practicable in the viewing telescope. It may be stated that, except with highly specialized apparatus of a standard or sub-standard quality, it is not normal to employ graduations separated by less than about 30 seconds of arc. Under such conditions it will usually be fairly simple to *estimate* between such divisions in steps of one-fifth, i.e. every 6 seconds.

Banks of Collimators. It is sometimes required, as for example in testing a theodolite, to be able to refer to a number of datum marks, in either the vertical or the horizontal plane, the distances between which subtend definitely known angles at the observing point. If there is a sufficiently wide field of view it is, of course, possible to use a number of prominent landscape features whose angles of bearing from the observation point have been accurately surveyed. This is an easier matter in the horizontal than in the vertical plane, but, in

any case, such a method can be used only in daylight, when there is clear visibility. A much more satisfactory "all the year round" arrangement is a bank of collimators set so that their optical axes make definitely known angles with one another. In setting up such a bank it is very important to ensure that there are periodical checks upon the actual angles, since small movements will certainly take place with changes of temperature and with age. The structure upon which the collimators are mounted should be rigid and not subject

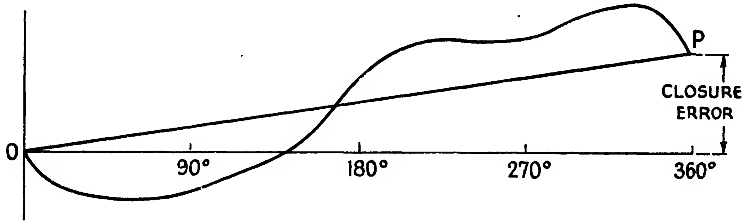


FIG. 43. COLLIMATOR CLOSURE ERROR

to distortion due to such causes as temperature changes, and if possible it is desirable to arrange for reasonable temperature control of the room in which they are situated.

It is not necessary to employ sufficient instruments in a horizontal bank to divide up the entire circle of 360°. Unless space should permit, it is sufficient to employ four or five only, and to rotate the observing instrument back in such a manner that the *last* reading is referred to the *first* collimator. By means of a repetition of this it is possible to complete a series of readings round the whole 360°. Under these conditions it will usually be found that there is a small error in the last reading. This will probably be due to an accumulation of errors in resetting the instrument each time that the end of the bank is reached. Under such conditions it is advisable to share the final error equally and proportionately between the various settings that have been made. Alternatively this may be considered graphically by means of Fig. 43. Suppose that the positive and negative errors are plotted against angles of reading as shown in the figure. Suppose, further, that this curve indicates some definite error, indicated by the point P, at 360°. Clearly this cannot be true, since the angle 360° is the same as 0°, so that (unless some unknown movement has taken place) the error at this point should be zero. Join the points OP and treat the line OP as though it were the base from which all errors are measured. This will, in general, be a very close approximation to the truth.

Auto Collimators. For some purposes it is convenient to incorporate the viewing telescope in the same instrument as the collimator, and to view the collimator image in some reflecting surface. The usual purpose of such an arrangement is to measure changes in the angle which the reflecting surface makes with some datum of reference. A typical instrument of this kind is the Angle Dekkor made by Adam

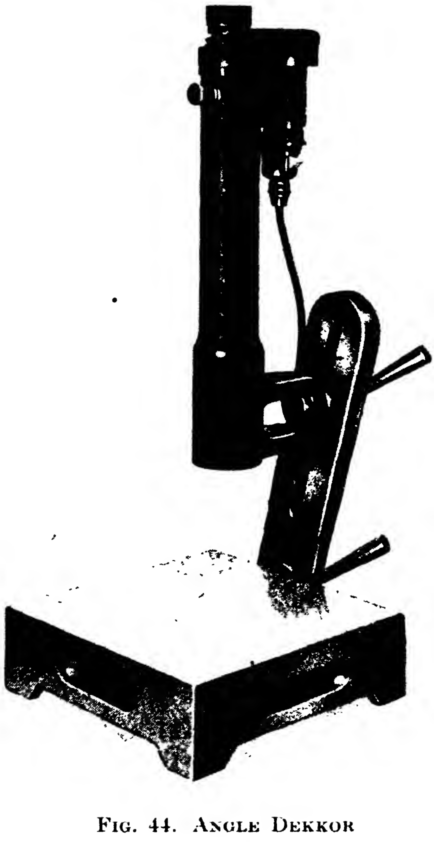


FIG. 44. ANGLE DEKKOR

Hilger, Ltd., and retailed by Alfred Herbert. This instrument is illustrated in Fig. 44, whilst Fig. 45 indicates the optical system. The viewing eye-piece contains a fixed scaled horizontal graticule, whilst the collimator portion of the instrument contains a scaled vertical graticule. The graduations are at one-minute intervals, and are illustrated in Fig. 46, which in (*a*) may be taken as indicating zero

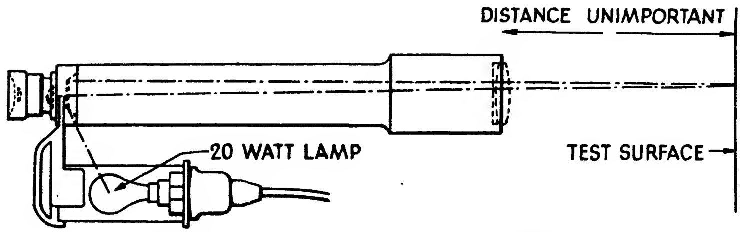


Fig. 45. Angle Dekkor Optical System

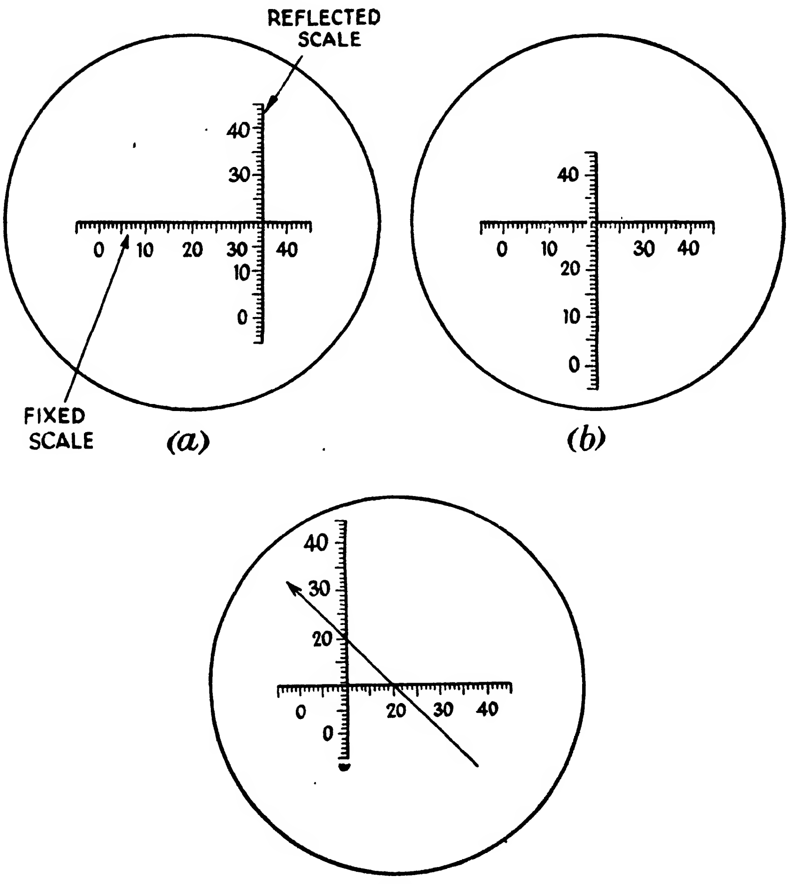


Fig. 46. Angle Dekkor Graduations

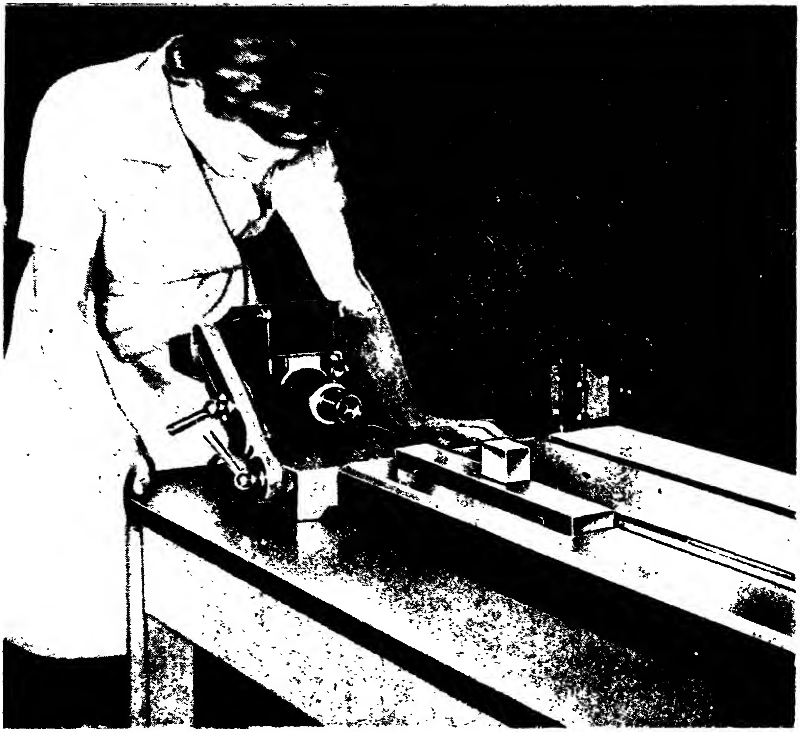
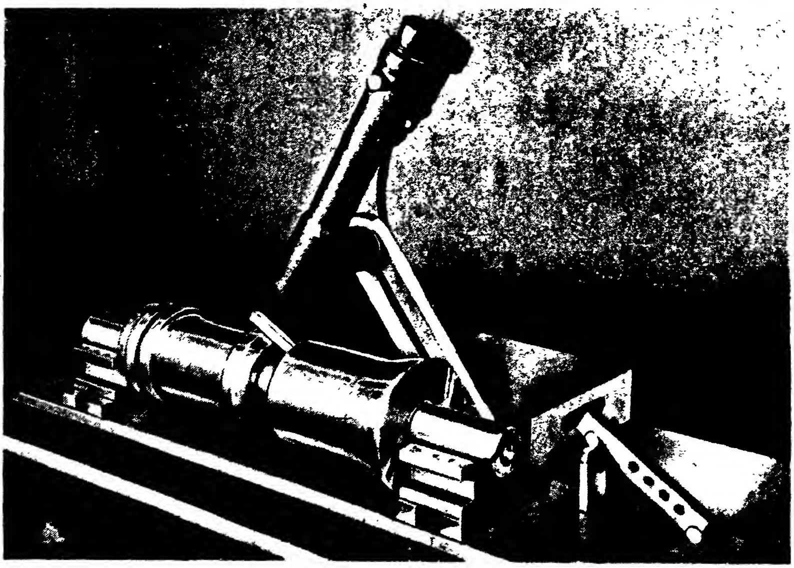


FIG. 47. DEKKOR TEST OF BASE PLATE



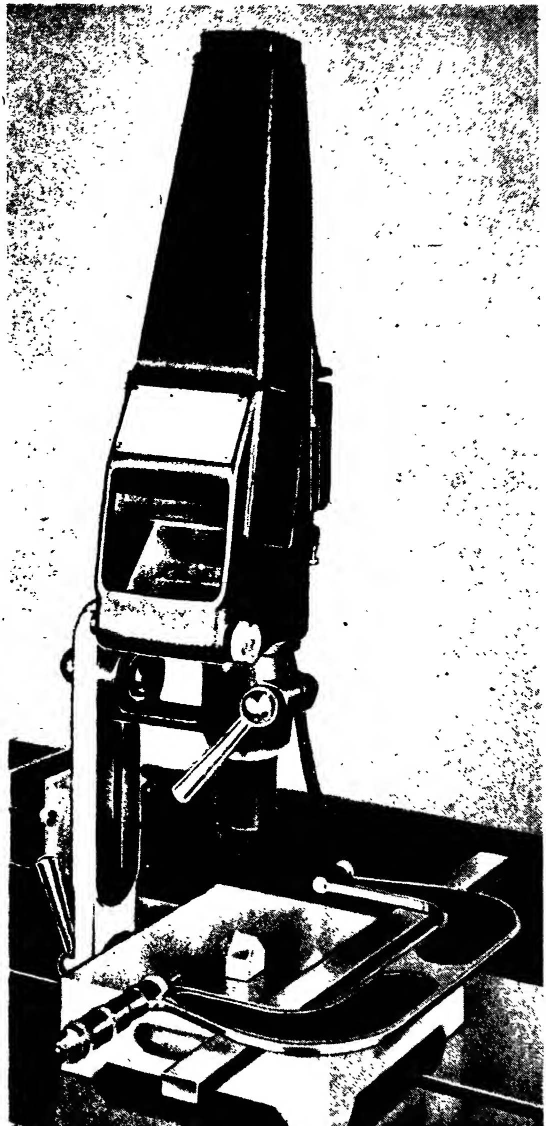


FIG. 49. DEKKOR TEST OF MICROMETER

deflection in the vertical direction. If now the reflecting surface is tilted forwards or backwards the reflected scale will move up or down with respect to the horizontal scale. Thus Fig. 46 (*b*) shows a tilt of 10 minutes. Similarly, any rotation of the reflecting surface about a vertical axis (i.e. in the horizontal plane) would cause a movement of the vertical (reflected) scale to right or left along the horizontal scale. Figs. 47 and 48 indicate two possible uses of the instrument.

Two other types of Angle Dekkor are obtainable. One of these is a larger instrument, which, in addition to possessing graduations only 30 seconds apart, may be used at distances up to 20 ft. from the reflecting surface, whereas the smaller instrument cannot be used farther than about 6 ft. The other design is similar to the standard instrument, but projects an image of the scales on to a screen in order to avoid eye fatigue when in use for long periods.

Fig. 49 indicates an interesting application of the instrument. An accurately polished "splitting prism" is shown on the stage, and it is being used to enable the observer to determine the parallelism of the anvil faces of the micrometer calliper shown.

CHAPTER VII

MEASURING LENGTH AND FLATNESS

THE problem of measuring length can present itself in a variety of different ways, and the type of test to be applied will depend upon the manner in which the problem arises.

Comparator. If it is desired to measure the length of a short rod, for example (or the like), it is possible to use some form of comparator in conjunction with appropriate slip gauges. The comparator was described in the previous chapter and its method of use will be obvious.

Vernier Slide Gauge. This type of instrument is used as a sub-standard for checking the dimensions of pin gauges, end measuring rods, and similar workshop or inspection gauges. Messrs. James Chesterman & Co. make such instruments in two sizes, one of which can measure lengths up to about 7 ft. and the other up to about 10 ft.

They are mounted on robust cast-iron bases and the Vernier can be read to 0·001 in. or 0·02 millimetre. Measurements of either internal or external dimensions may be made, and are taken either from hardened steel plugs or from flat jaws which may be substituted. Although robust, they are highly finished instruments, and the accuracy is that normally expected from an instrument fitted with a high-precision Vernier.

P.V.E. Stick Micrometer. During the war there was a demand for instruments suitable for making accurate measurements over several feet, particularly in connexion with the manufacture of aircraft, tanks, cars, bridges, and the various jigs and fixtures used in the manufacture of these, in order to ensure interchangeability of the various components. This requirement can be met, in most instances, by the use of what has come to be known as a stick micrometer.

This instrument, which is illustrated in Fig. 50, and which is made by the Pitter Gauge & Precision Tool Co., consists of a micrometer head, reading in 0·001 in. increments, a 1-in. spherical end-piece and 1-in., 2-in., 3-in., 5-in., 12-in., and as many 24-in. pieces as may be necessary to make up any length required. Units of corresponding metric increments are also supplied.

The various pieces and the micrometer head may be joined to each other by means of a swivelling screw at one end of the piece and the tapped opposite end. These swivelling screws ensure the end faces

of the various pieces meeting each other squarely. Each piece consists of a steel tube, hardened at each end and accurately lapped to length, having a bakelite insulating tube covering, supported at its ends by bakelite ferrules. This construction forms an air gap between the insulating tube and the steel tube; the former is allowed end movement, and may turn freely in the ferrule supports. Only the ferrules are fixed to the steel tube and are used for screwing together the various

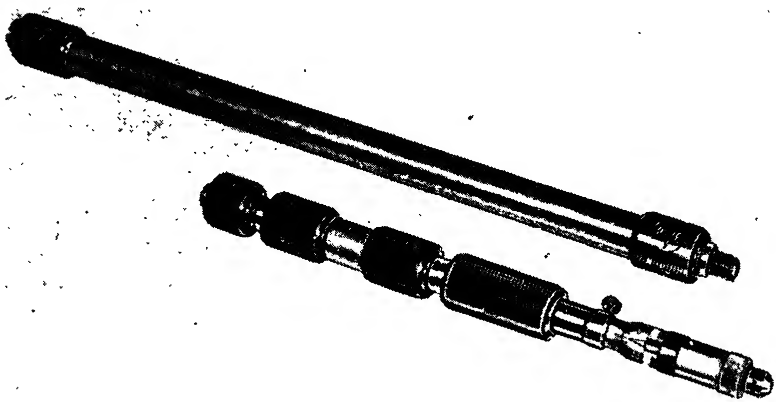


FIG. 50. STICK MICROMETER

sections of the stick; their position at the ends of the sections precludes the possibility of causing torsion in the steel tube in the process of screwing-up.

An accuracy of + 0·0002 in. minus nothing is maintained for the 24-in. pieces and 12-in. pieces, and + 0·0001 in. minus nothing for the remainder, whilst a setting piece is provided to check the accuracy of the micrometer head and spherical end. Thus in a 20-ft. length an accuracy of + 0·002 in. minus nothing may be maintained provided, of course, that it is supported in a straight line. The reason for the tolerance being "plus" only is to ensure a longer life.

Measuring Microscope. This type of instrument is somewhat similar to a toolmaker's microscope (see previous chapter) but the mechanism is slightly different. That produced by the Cambridge Instrument Company is shown in Fig. 51. It is designed for the accurate measurement of lengths up to 40 millimetres, and can be read directly to 0·01 mm. or, by estimation, to 0·001 mm. The work is carried on a small

table which may be slid on geometric fittings. A rotating table (not shown) may be fitted for measuring polar co-ordinates.

The microscope is clamped to a tube and is traversed by means of a lead screw and milled head. One very useful application of such an instrument is the measurement of the pitch of small screws and the determination of variations in this pitch. In certain cases it is a convenience to have two microscopes and such an arrangement can be

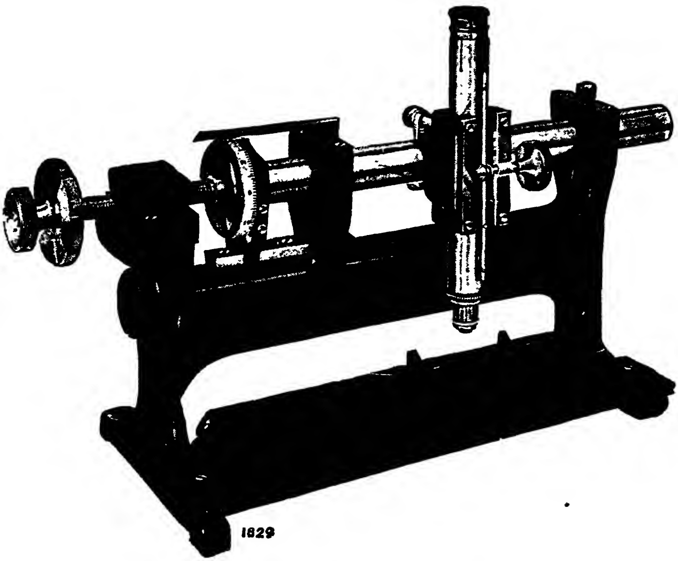


FIG. 51. CAMBRIDGE MEASURING MACHINE

obtained if required. These instruments may be supplied with graduations in inches instead of millimetres.

Measuring Machines (Lead-screw Type). This type of machine permits a very accurate measurement of length, and one made by the Newall Engineering Company is shown in Fig. 52. The designers claim that attempts have been made to avoid all possibility of error, whilst at the same time making no demand for special care or training in operation. The beds, headstock, and tailstock are all made of close-grained cast iron, hollow to permit free circulation of air, and seasoned over a long period to prevent warping owing to stress relief on ageing. The beds rest on three points to avoid distortion. True surface is maintained by the beam form coupled with the positioning of the feet in such a manner that the load is equalized throughout.

Fig. 53 shows a close view of the headstock and tailstock. The headstock carries the measuring screw with reading drum and Vernier. This screw has a range of 1 in. or 25 millimetres according to whether

FIG. 52. NEWALL MEASURING MACHINE

it is an English or metric machine. The threaded portions of the screw and its nut are equal and of about 3 in. length. This fact, coupled with the use of a deep thread, provides for small and even wear and the

FIG. 53. NEWALL MEASURING MACHINE (CLOSE VIEW)

retention of pitch accuracy. The nut and screw surfaces are automatically maintained in constant contact pressure, and backlash is avoided. Although the screw is very accurately cut, a secondary screw of the same pitch is arranged in such a manner that the slight errors which exist are automatically compensated by forwards or backwards motion imparted to the Vernier.

For measuring sizes greater than the range of the measuring screw the position of the tailstock is set by means of what the manufacturers call a micro-locator. This is shown in Fig. 54, and rests in the appropriate position on a series of rollers similar to those employed in the jig borer made by this firm and described in the previous chapter. A microscope carried on the tailstock is sighted on to a mark on the micro-locator. (Fig. 54 shows rollers fitted to a machine suited to either English or metric units.)

The tailstock carries a fiducial stop in the form of a spirit level. When pressure is applied to the anvil, through the piece being measured, a tilt is imparted to the level and the bubble movement represents a 4000 to 1 magnification of the anvil movement, thus permitting very accurate setting. It is possible by this means to allow the work to rest in the machine and note when its temperature has stabilized after being handled, since contraction during cooling will cause the bubble to move until steady conditions are reached.

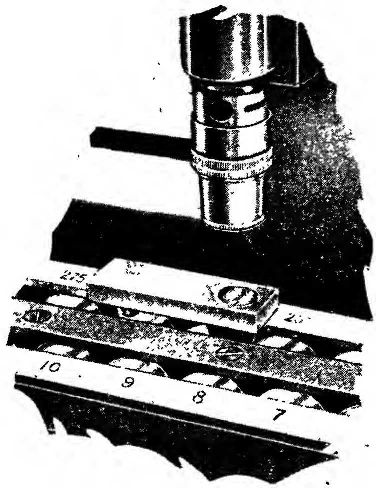
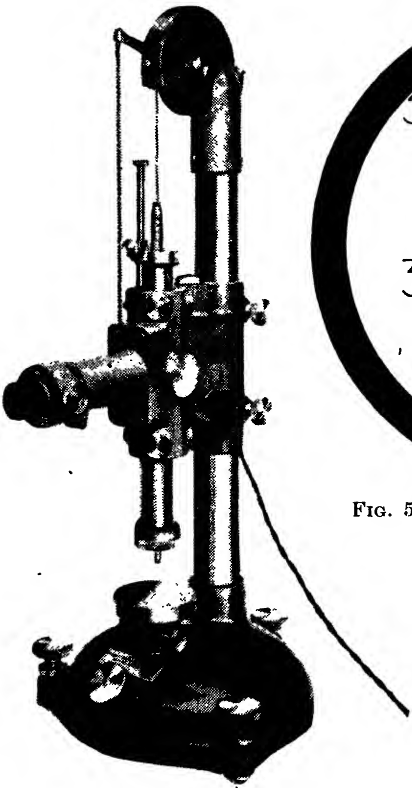


Fig. 54. Newall Measuring Machine Locator

These machines are made in various sizes up to 12 ft. in length, and accuracies similar to those on a jig borer may be obtained. The Vernier head reads to 0·00001 in. or 0·0001 mm.

Measuring Machine (Optical Type). Messrs. E. R. Watts & Son have developed a machine for measuring from 0 to 4 in. directly to an accuracy of 0·0001 in. or, under suitable conditions, 0·00002 in. This machine is illustrated in Fig. 55, and is known by the firm's trade name of the Microptic Measuring Machine. It is, in some sense, similar in action to a comparator, but the plunger, instead of acting upon a dial indicator, carries a straight glass scale accurately engraved from 0 to 4 in. in steps of 0·05 in. This is viewed by means of a microscope in whose field of view there is a fixed graticule divided into steps each representing 0·01 in. and movable in the vertical direction, so that one of its divisions may be made to coincide with a reading on the main scale. This movement is produced by means of a milled head on

the right of the eye-piece. In addition to this there is, in the field of view, another scale whose whole length corresponds to 0·01 in. subdivided into 200 parts so that each subdivision represents 0·00005 in. the rotation of the milled head causes this second (micrometer) scale



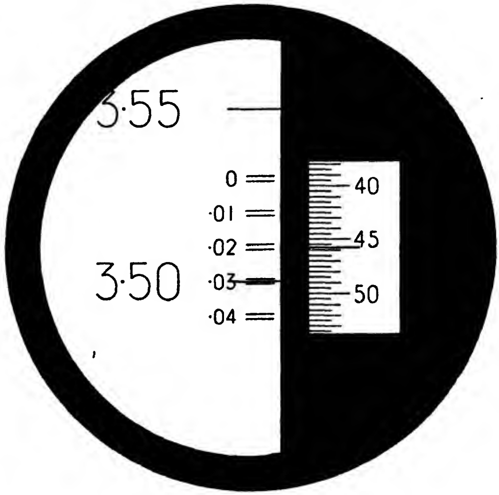


FIG. 56. OPTICAL MEASURING MACHINE (FIELD OF VIEW)

FIG. 55. OPTICAL MEASURING MACHINE

to move over a fixed fiducial line so that it is possible to determine the amount by which the main graticule has been moved to bring it on to a reading. Fig. 56 shows the field of view and the reading indicates 3·53458 in.

The work table is $3\frac{1}{2}$ in. in diameter worked to a flatness of 0·00002 in. It is adjusted to "zero" height by means of a knurled knob at the base of the instrument. The measuring plunger runs in ball-bearing rollers, is supported by a flexible wire which runs over a pulley, and has its other end attached to a counterweight, leaving the plunger with a preponderance of 12 oz. Descent is controlled by oil damping. The plunger is raised by means of a chain and knob which act through a lever and gearing upon the pulley axle, thus avoiding touching the plunger with the fingers.

The glass scale is very stable, and free from the "creep" suffered by metals under ageing. The temperature coefficient is 0·000003 per degree centigrade. Graduations are made to an accuracy within 0·00001 in. but, since the scale is calibrated before issue, even these

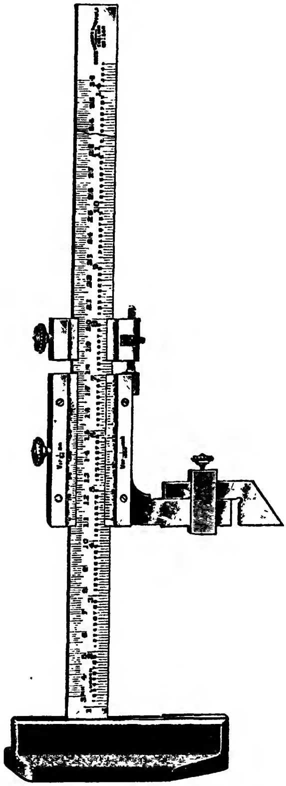


FIG. 57. HEIGHT GAUGE

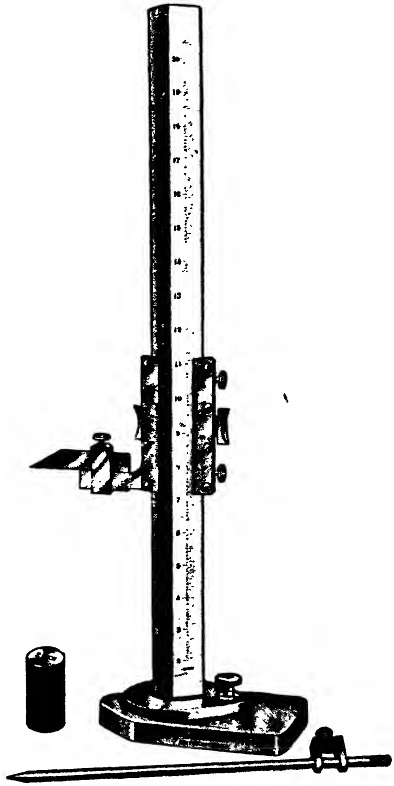


FIG. 58. PRECISION HEIGHT GAUGE

errors may be taken into account. If the room temperature is controlled within $\pm 2°$ F. of the standard 68° F., accuracies within 0·00002 or less are possible.

Height Gauges. It is frequently necessary, either for purposes of marking out or else to measure existing work, to ascertain the height above the base of some particular point on a jig or fixture. In such cases the work to be measured is placed upon a good-quality surface plate and a height gauge is used.

Fig. 57 shows a typical instrument of this type, the particular one shown being manufactured by James Chesterman of Sheffield. It is

scaled on one edge in English, and on the other in metric units, and it can deal with work up to a maximum height of 12 in. The Vernier is arranged with the customary fine adjustment device, and can be read to 0·001 in. or the equivalent in millimetres.

A higher grade article produced by the same firm is shown in Fig. 58. This may be obtained in various sizes up to 1 metre in height. The beam is of V instead of flat section, thus providing greater rigidity, and slow motion is obtained throughout the whole vertical travel by means of the knurled knob at the base. Quick approximate setting may be made by operating the disengagement device at the sliding head.

In using a height gauge, as indeed with all work requiring a surface plate, it is essential that this latter should be of high quality and in perfect condition, since any imperfections will be reflected as inaccuracies in measurement. Grade A surface plates have a flatness accuracy of the order of 0·0002 in. It is, however, possible to obtain toolmakers' surface plates lapped flat to 0·00001 in. in a 12 in. square size. It is advisable that there should, from time to time, be a test for any zero error on the height gauge scale. This is very readily done by means of slip gauges.

Depth Gauges. When it is necessary to measure the depth of some point below a reference surface, as, for example, the depth of a counter-bore, use is made of a depth gauge The rule, which may be obtained in a variety of lengths and graduations, is adjusted till it rests at the bottom of the hole or counter-bore. Measurement is made directly on the scale against the hardened stock through which the rule slides.

Where more accurate measurement is required a micrometer type as shown in Fig. 59 is used. The instrument illustrated is made by Messrs. Moore & Wright and, as will be seen, is supplied with a range of rods of different lengths.

Fig. 60 shows an instrument which is very useful where a comparator type is required. As will be seen, readings are obtained on a sensitive dial indicator. The instrument illustrated is one of a range manufactured by Messrs. J. E. Baty & Co., Ltd.

Optical Reading Instruments. In order to overcome some of the errors possible where metal scales, Verniers, etc., are employed, Messrs. E. R. Watts have brought out a series of instruments such as height gauges, Vernier callipers, etc., employing linear glass scales viewed by means of a microscope similar to that described on page 73 under the heading Measuring Machine, Optical Type. All such instruments are produced under Messrs. Watts's trade name Microptic.

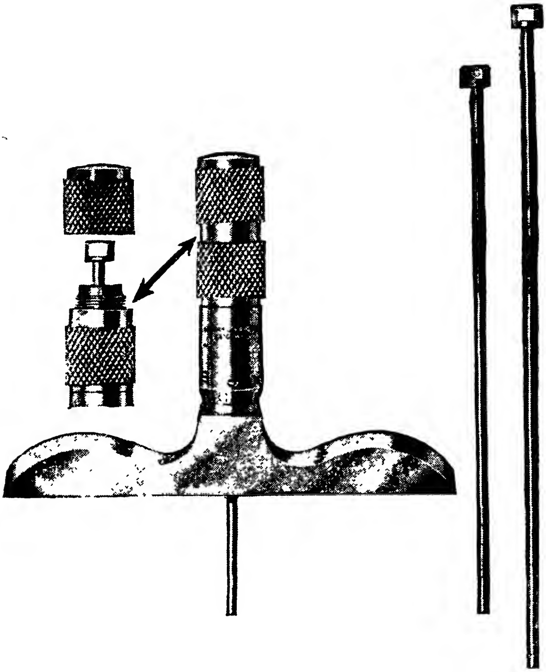


FIG. 59. MICROMETER DEPTH GAUGE

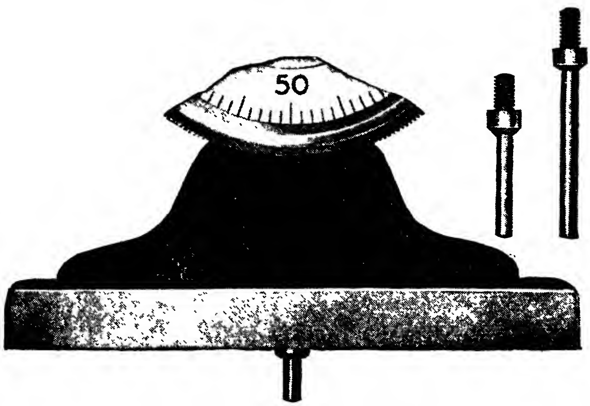


FIG. 60. DIAL DEPTH GAUGE

Special Purpose Test Fixtures. In Chapter I we saw that the inspection department will, during the process of "tooling-up" by the production department, have planned the inspection and designed any necessary special purpose test jigs or fixtures. Fig. 61 shows an incomplete mechanism which is a component of a complicated instrument.

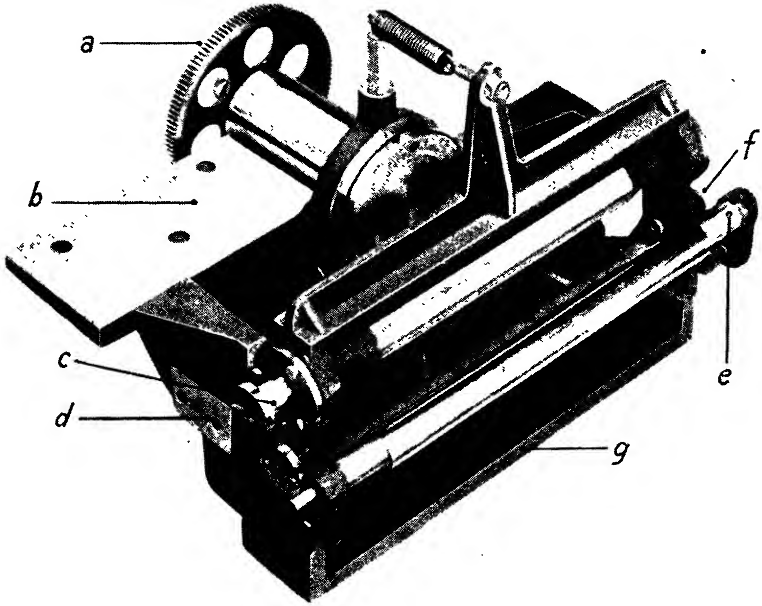


FIG. 61. MECHANISM FOR TEST

It is designed to bolt to a base plate and, when in position, it is required to fit together with other component assemblies. Some of the various points requiring inspection are as follows—

1. Gear wheel *a* must be in correct position both in plan and height.
2. The holes in surface *b* must be in correct position in regard to one another.
3. The spindle end *c* must be correctly situated, and the slot in its end must be correctly engaged by the blade on the other half coupling with which it has to mate.
4. The two holes in surface *d* must be correctly positioned.
5. The spindle *e* must be at the correct height and be mounted so that the concentric portion at the end rotates truly. (The throw of the cam portion is tested by other means, not shown.)

Figs. 62 and 63 show two views of the test fixture which was designed for inspecting this component. The letters in these two figures correspond with the parts of the component which they test.

The finished component is placed flat upon the base plate with its front edge g butting against the flat edges of the two studs G (see Figs.

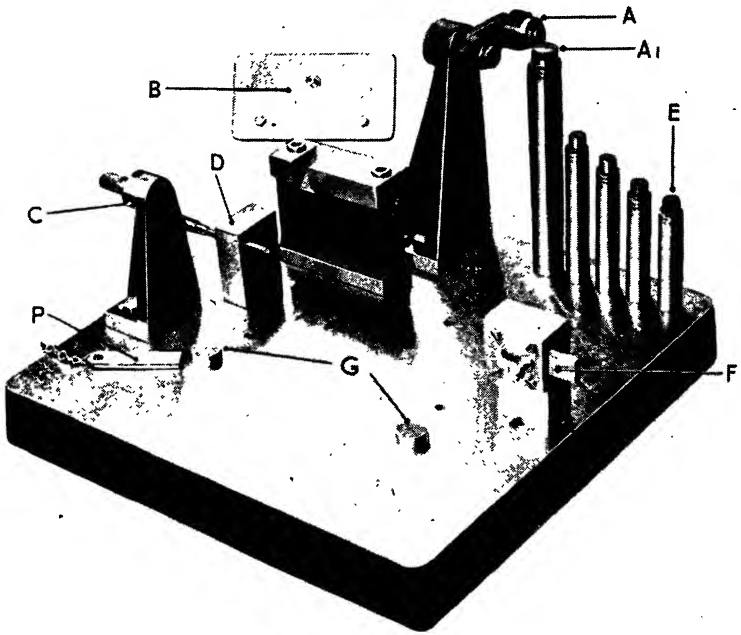


FIG. 62. TEST FIXTURE FOR FIG. 61

64 and 65). It is positioned laterally by bringing it up to the point where the surface d makes contact with the inner surface of the pillar D.

The various items of inspection enumerated above are carried out as follows—

1. The accurately thread ground worm A is swung over so as to engage with the gear wheel a. The anvil of a clock indicator supported on a stand (not shown) is brought to bear upon the plain portion of the worm, which is then rotated, thus causing a to rotate. Any radial errors in a, due, for example, to eccentricity, will be shown on the clock dial. The actual height of a is checked by passing the clock indicator from A to the pillar A_1, which is ground to the correct dimension.

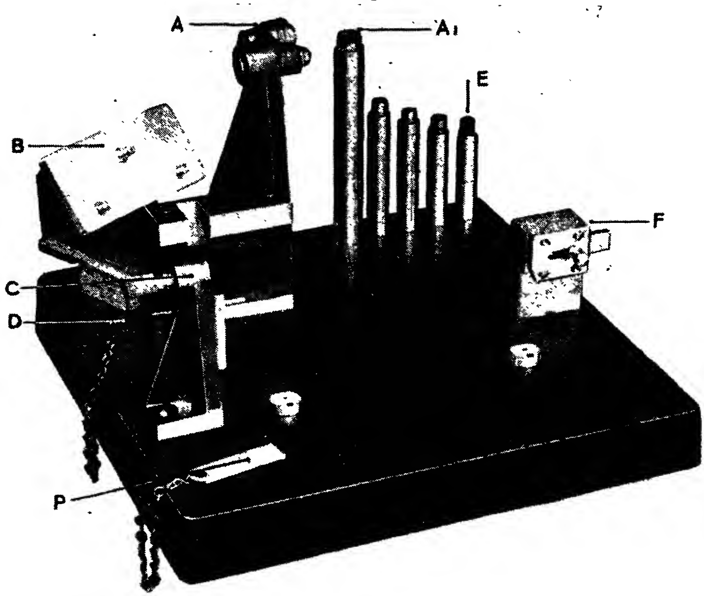


FIG. 63. ANOTHER VIEW OF FIG. 62

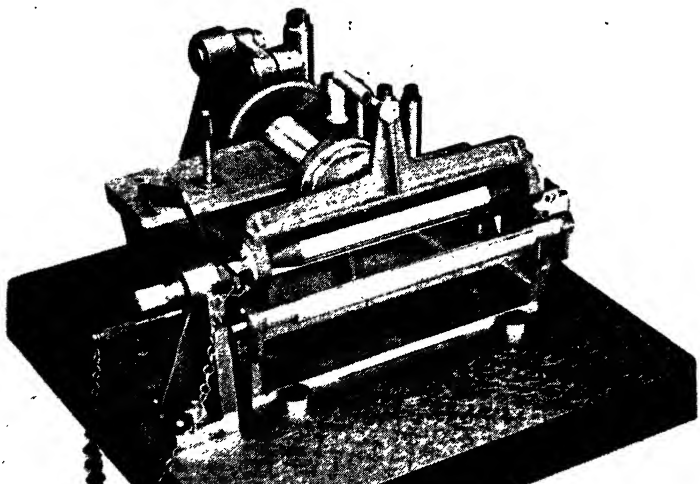


FIG. 64. MECHANISM IN TEST FIXTURE

2. The plate B is, in fact, loose. It is shown in Figs. 62 and 63 supported by some wooden blocks merely for clarity. This plate is brought into association with the surface b so that the two studs register through the appropriate holes into those in the fixture. The third hole is checked by means of the plug pin as shown.

3. The blade in the top of bracket C (seen most clearly in Fig. 63),

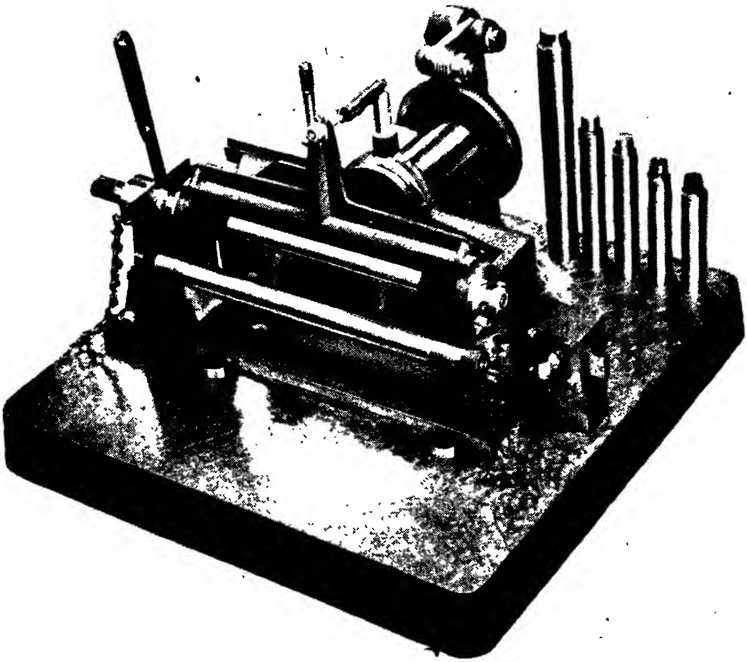


FIG. 65. ANOTHER VIEW OF FIG. 64

which may be withdrawn by means of the knurled head, must engage correctly with the slot in spindle end c in the two positions (i.e. when rotated through 180°). The endwise position of the spindle face is checked by the insertion of the distance piece P. When this is in position it should be possible to insert feeler gauges to a (suitably toleranced) thickness.

4. The two holes in surface d are checked by the insertion of the pin through the two holes in pillar D.

5. The concentricity and height of the end of spindle e are checked by means of a clock indicator in association with pillar E in the same manner as was done in test (1).

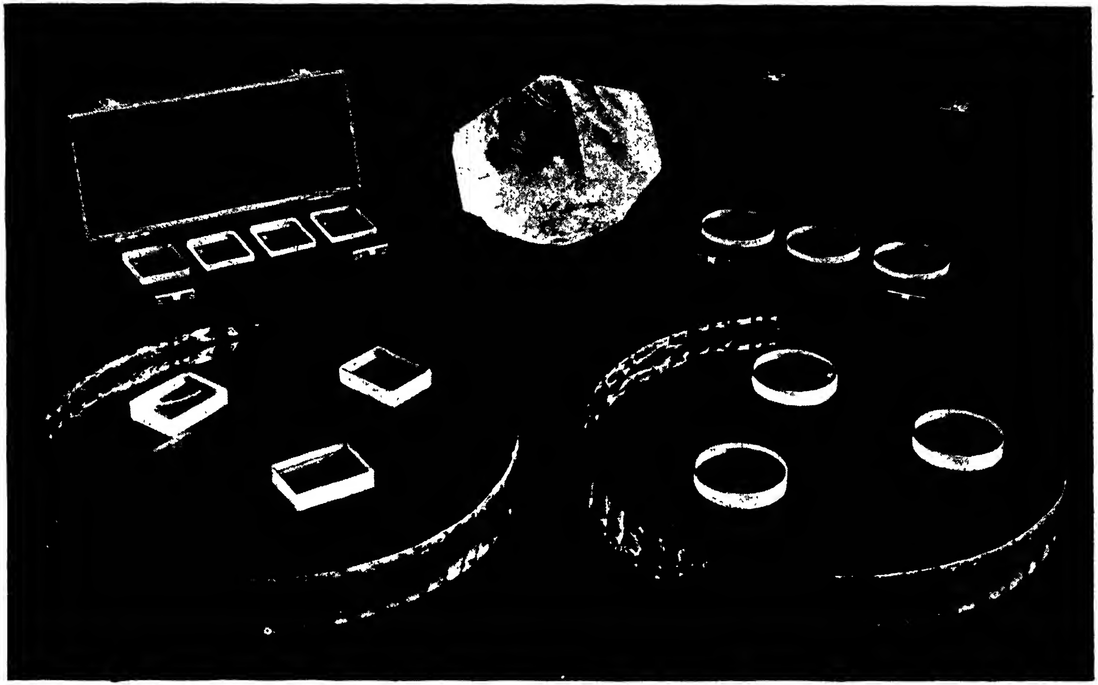


Fig. 66. Optical Flats

It will be clear that, in the construction of the test fixture, the greatest possible care will have been exercised in accordance with best tool room practice. Thus it will be seen that all pillars, etc., are dowelled in addition to being bolted in position. Test holes are fitted with hardened bushes. All dimensions are toleranced approximately ten times more closely than that allowed to the mechanism under test.

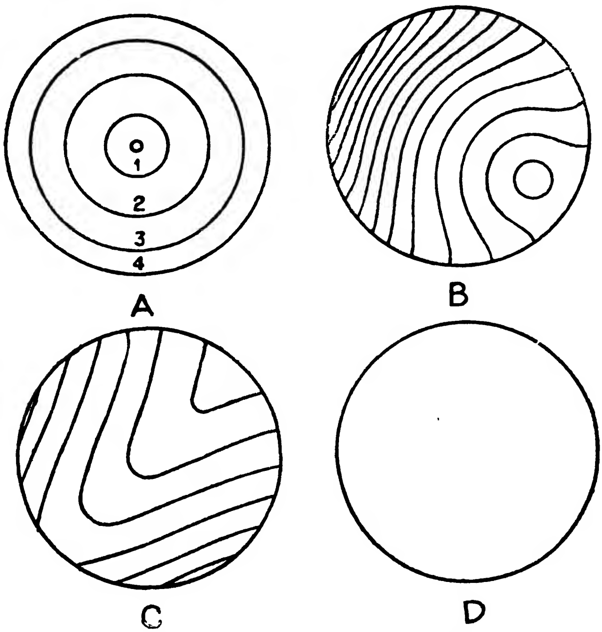


FIG. 67. OPTICAL FLAT PATTERNS

Optical Flats. These are usually quartz discs worked to a very high degree of flatness, which is of the order of 2 millionths of an inch. Their method of use depends upon the fact that, if two optical surfaces be separated by a thin layer of air which is, however, not of uniform thickness, the reflected beam of light will be split into its various colour components and will appear as a series of miniature rainbows. It can be proved that the difference in thickness of the air films at two neighbouring "rainbows" is 0·0000103 in. so that, by measuring the distance from one "rainbow" to the next (taking care to measure between bands of the same colour, usually red), we have an exact method of investigating the dimensions and character of the space between the two surfaces.

Fig. 67 shows, diagrammatically, the appearance of colour fringes for different surface conditions.

(A) The fact that the rings are farther apart in the centre than at the edge means that the surface at the centre is more nearly parallel to the test flat than is that at the edge. This does not distinguish between convexity and concavity. If, however, the flat is pressed lightly at the centre with a finger-tip, the fringes will move away from the finger if there is a hill or towards the finger if there is a valley.

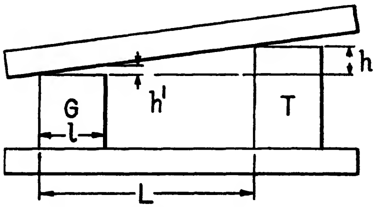


FIG. 68. TEST BLOCK CHECK BY OPTICAL FLATS

(B) This surface is either convex or concave near the lower right hand. The finger-tip test will decide which it is.

(C) A ridge or a valley runs across a diameter from South-West to North-East. Finger-tip test decides between ridge or valley.

(D) A perfectly flat surface in close contact with the optical flat.

Checking a Test Block having Flat and Parallel Faces. The flatness of the faces can be tested by means of the optical flat in the normal way. In Fig. 68 G represents the gauge and T the block under test. They should be placed at a known distance apart wrung on to an optical flat. A second optical flat is applied to the upper surfaces. Assuming that there is a small difference in height between G and T, there will be small wedges of air between the optical flat and the upper surfaces of G and T respectively. This will give rise to a series of parallel straight colour fringes at each wedge, as shown in the left-hand side of the figure. Since the wedges are of equal angle the colour fringes will be equally spaced in the two sets.

Let L = distance between similar edges of G and T.

l = width of G.

h = amount by which height of T exceeds that of G.

h' = height of optical flat above right side of G.

N = number of colour fringes at G.

Then
$$h = h' \times \frac{L}{l}$$

Also, since the difference in thickness of the air between neighbouring colour bands is 0·0000103 in., we see that

$$h' = 0{\cdot}0000103\,N$$

hence

$$h = 0{\cdot}0000103\,\frac{NL}{l}$$

Checking a Test Block having Flat but not necessarily Parallel Faces. In this case the angle made by the optical flat with the upper surface of T will not be the same as that made with the upper surface of G. The number of colour fringes will therefore be different in the two cases. It is, however, a matter of very elementary geometry to apply to this case the method already outlined.

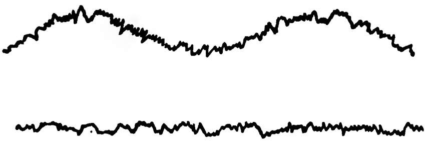


FIG. 69. SURFACE WEAR

Optical flats are usually supplied in sets of three, since such a set provides a means of self checking in order to ensure that the flats are truly flat and not merely equally spherical. Quartz is better than glass since, for one thing, it is less affected by temperature and, for another, minute scratches do not raise ridges, whereas with glass they do so and thus affect the accuracy. We have already indicated in a previous chapter that care should be taken to see that temperature effects of handling are avoided or else time must be given to allow cooling before making observations.

Tomlinson Surface Finish Recorder. Any machined surface will always consist of a series of more or less minute hills and valleys in either a straight or a wavy line, as shown in Fig. 69.

The wear which takes place at such surfaces consists first in the smoothing of the minute irregularities followed by the flattening of the "waviness" if present. This naturally causes an increased clearance between mating parts. Where it is desirable to investigate the quality of a surface, a mechanical instrument devised by the late Dr. G. A. Tomlinson of the National Physical Laboratory is ideal for the purpose. This instrument, which is made by Messrs. Baty of London, is shown, together with close view of the recording mechanism, in Fig. 70.

The instrument is entirely mechanical in operation, and the surface irregularities are recorded on a smoked glass plate. The record on the smoked plate is then magnified optically and examined directly at the screen of a projector.

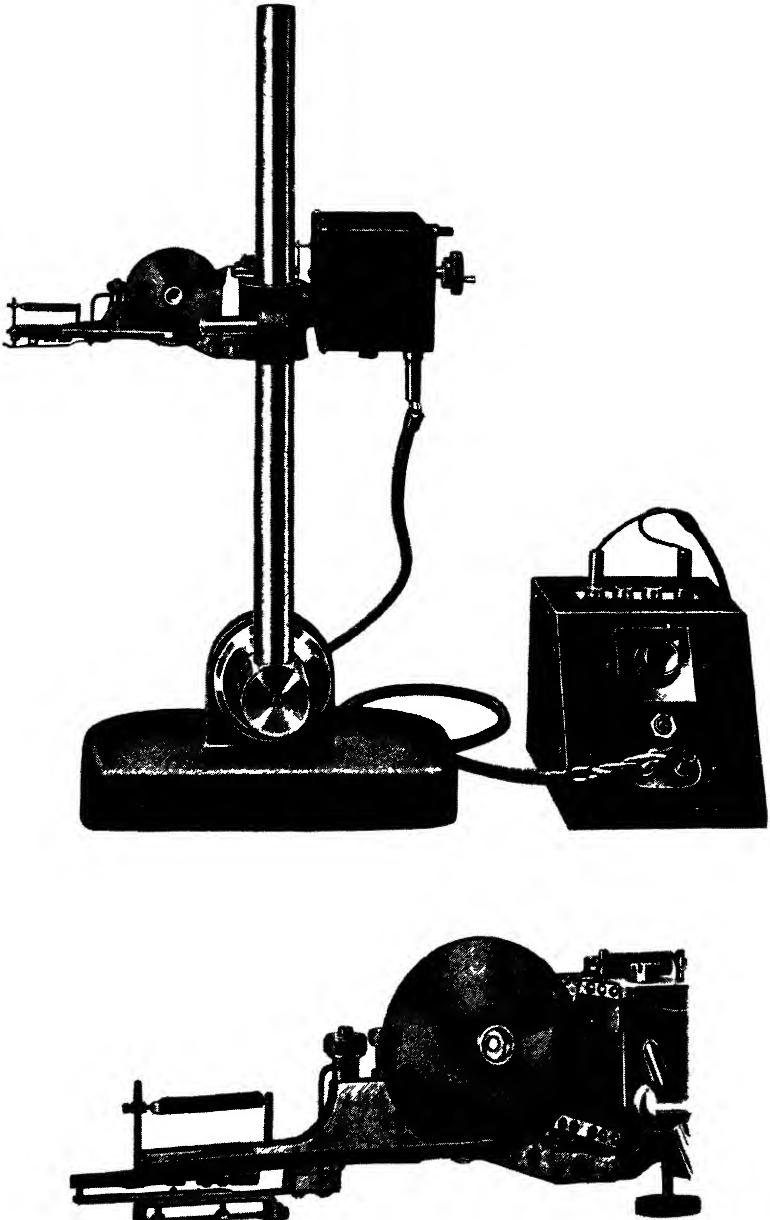
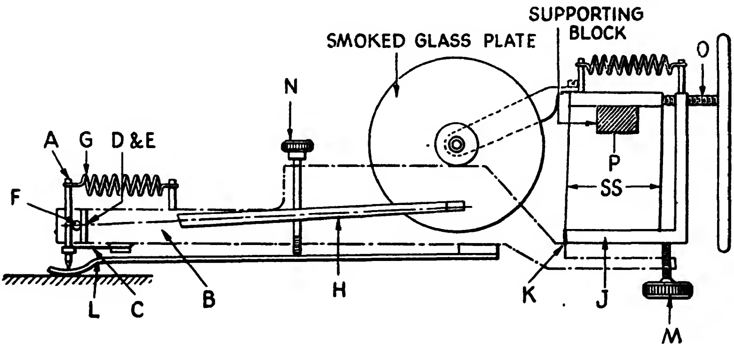


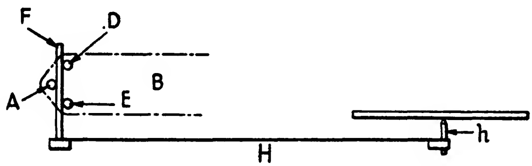
Fig. 70. Tomlinson Surface Recorder

The principle of operation is illustrated in Fig. 71, which is reproduced by courtesy of the Director of the National Physical Laboratory (Crown copyright reserved).

A diamond point is provided on the lower end of a vertical needle A. This needle is connected to the underside of the frame B by means



CLOSE VIEW OF FIG. 70



TOMLINSON RECORDER, PRINCIPLE

FIG. 71

of a flexible strip C. Two fixed vertical needles D and E are pressed lightly into the end of the frame and, between these and the exploring needle A, a fourth needle F is placed in a horizontal position. The needle F has attached to it an extremely light arm H carrying the recording point h. As the exploring point of A rises and falls in following the surface unevenness, the needle F rolls to and fro, so that the recording point h moves proportionately to the exploring point, the magnification being the ratio of the length of H to the diameter of F.

The movement along the surface is obtained by the rotation of the screw O, which is turned at a uniform slow rate by an independent motor drive through suitable reduction gearing. This action imparts a linear motion to the back part of the frame J, which is slung by two steel strips SS from the supporting block P. The length of horizontal traverse of the recorder is about 0·1 in.

It has been found that a magnification of 10,000 normal to the surface, i.e. 100 mechanical × 100 optical, is in general sufficient to show quite clearly the fine surface irregularities due to different machining processes.

P.V.E. Surface Analyser. The Pitter Gauge & Precision Tool Co. have recently developed an instrument for optically exam-

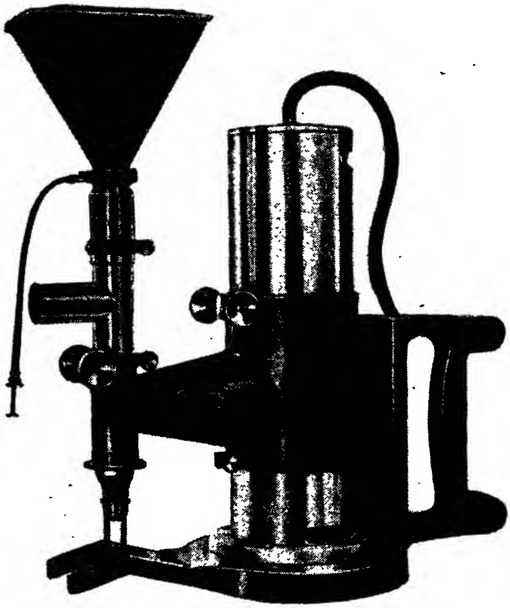


FIG. 72. P.V.E. SURFACE ANALYSER

ining the condition of surfaces, and by means of it irregularities of only a few millionths of an inch may be detected. It is illustrated in Fig. 72, and may be used either for making visual examination or for obtaining photographic records. The principle of operation is that outlined above under the heading "Optical Flats." Monochromatic light from a sodium lamp is used so that the image shows bands, not of the complete spectrum, as with white light, but only of the sodium yellow.

Although, clearly, the instrument is suitable for examining any type of finely finished surface, one of its main uses, perhaps, is for examining the finish of such articles as plug or slip gauges. An optically

worked quartz or glass slip is laid on the portion of the surface to be examined, and the "wedge" of air between the two gives rise to the fringes or bands as already described, except for a slight departure in technique. Where a cylindrical surface is being examined, as, for example, that of a plug gauge, a *flat* slip is used, which therefore includes a wedge of air the angle of which increases as we move farther

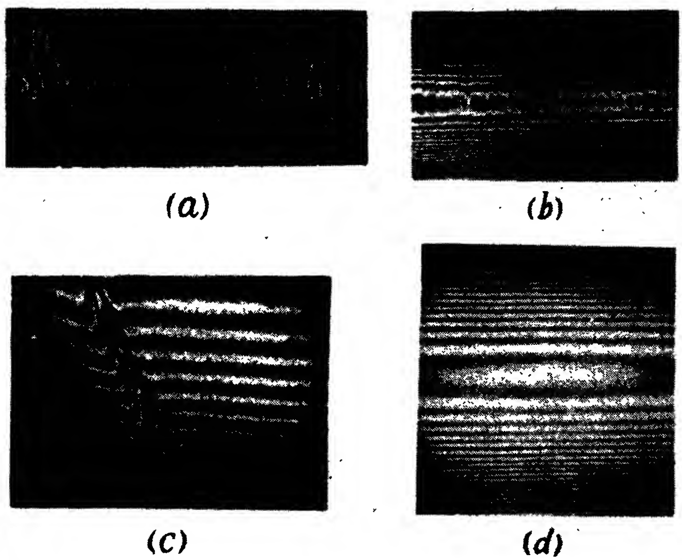


FIG. 73. SURFACE FINISHES

from the line of contact. The result is a series of light and dark bands which become closer together the farther away from the centre. Where a flat surface is to be examined the slip is one which has been accurately worked to a convex cylindrical finish, thus giving the same optical effect as before. The record is self-scaling, since the difference between the thickness of air under neighbouring bands is accurately known. The purity of the surface is indicated by the "cleanness" and straightness of the bands.

Fig. 73 shows records of four different quality surfaces.

(*a*) is a ground surface, not of the best finish, which had superimposed upon it a number of grooves caused by an out-of-balance wheel;

(*b*) is a fine ground finish;

(*c*) is a ground and lapped surface upon which is a fine scratch about 20 millionths deep, at the sides of which burrs have been raised to a height of about 4 millionths;

(*d*) is the record of the surface of a P.V.E. optical flat.

For the satisfactory interpretation of records taken by means of this instrument it is, naturally, important that the "slips" which are used should themselves be free from blemish.

Flatness by Spirit Level. Whereas the two previously described methods of employing a surface do so in detail, it is sometimes required to investigate the *general* flatness of a surface apart from minor local irregularities. A case in point would be the bed of a lathe, in which it is, naturally, necessary that the saddle shall traverse without deviation from the (horizontal) plane. A quick and simple means of checking this is to place a sensitive spirit level on the saddle. It is suggested that the sensitivity of the bubble should be at least as good as to give a deflection of one division for a tilt of 10 seconds of arc. If, now, the saddle be at one end of its travel and the whole machine adjusted so that the bubble is level, any departure from level will be shown by the bubble as the saddle is traversed from one end to the other. If desired, it is a simple matter then to "map" the general run of the surface.

Flatness by Angle Dekkor. A method similar to that using a spirit level is one in which a (vertical) reflecting surface is substituted for the spirit level and its angle observed by means of an Angle Dekkor. The details of this method will be obvious after reading the description of the instrument given in Chapter VI.

CHAPTER VIII

MEASURING DIAMETER

Callipers. A straightforward but not very accurate method of measuring diameters, internal or external, is by means of suitable callipers, a few different types of which are shown in Figs. 74 and 75.

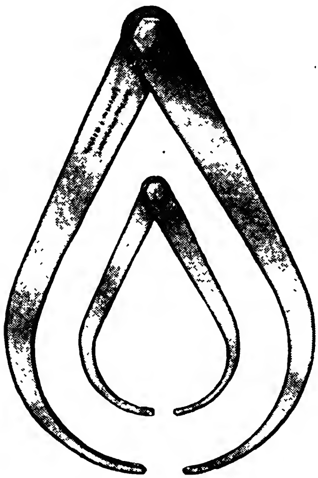


FIG. 74. CALLIPERS

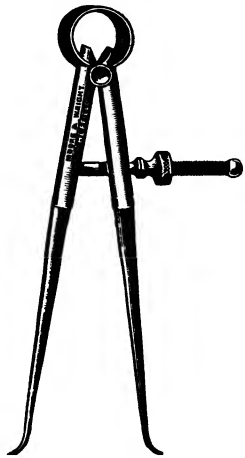


FIG. 75. SPRING CALLIPERS

Such instruments may be used for making comparisons of diameters or else, in conjunction with a suitable scale, for making direct measurements.

Vernier Callipers. Where a greater degree of accuracy is required a Vernier type of instrument will be used, and Fig. 76 illustrates such an instrument manufactured by Messrs. James Chesterman. A variety of sizes may be obtained. It will be seen that the normal slow-motion device is provided for fine setting. The beam is hardened and tempered whilst the jaws, which are glass hard, provide for either internal or external measurement. By means of the Vernier, readings may be taken to 0·001 in. or 0·02 mm.

Internal Micrometers. An internal diameter may be measured by means of a suitable expanding micrometer such as was described in Chapter VI and illustrated in Fig. 21. Internal micrometers may be obtained, using three instead of two points, and, further, such

instruments are manufactured with a dial indicator instead of a micrometer head. This last type is especially useful where bores of more or less a definite size require to be measured.

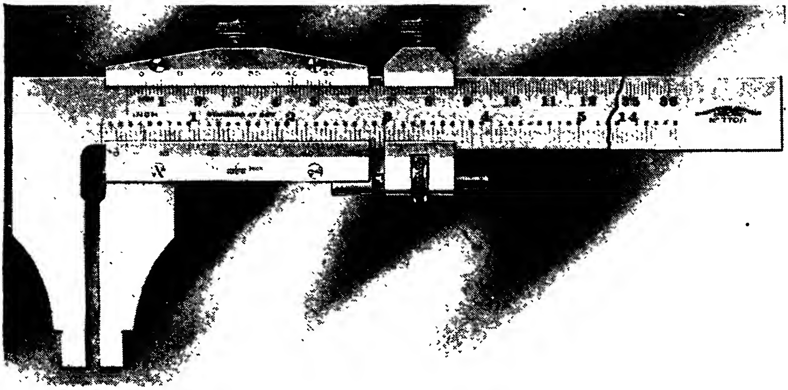


FIG. 76. VERNIER CALLIPERS

Cylindrical Gauges. The normal type of standard gauges for internal and external diameters will be plug and ring gauges respectively, as shown in Fig. 77. These gauges will be made of tool steel hardened,

FIG. 77. PLUG AND RING GAUGE

ground, and lapped to within the appropriate limits to the plan size. We have already discussed the principles upon which these limits are decided. Thus the N.P.L. grade A limits for different diameters are as follows—

Up to 1 in.	plus and minus 0·00005 in.
Between 1 in. and 2 in.	plus and minus 0·0001 in.
Between 2 in. and 4 in.	plus and minus 0·00015 in.
Between 4 in. and 6 in.	plus and minus 0·0002 in.

Such gauges may be obtained in a large variety of standard sizes,

either in English or in metric units, and can, naturally, be obtained in special sizes to order.

Taper gauges of similar types may also be obtained.

Classes of Fit. This expression normally refers to cases of shafts in holes. Thus, for example, we may be considering a journal running in a bearing, in which case, for free running, the diameter of the journal will be less than that of the bearing, or else we may be considering a collar which is required to be a tight fit on a shaft, in which case the diameter of the latter will be *greater* than that of the collar, which will require to be forced into place.

We saw in Chapter IV that the dimensions of holes may be given in such a manner that the plan size of the hole constitutes the lower limit. In this case the system is called unilateral. On the other hand, the limits may lie on either side of the plan size, in which case the system is bilateral. The former is known as a U hole, whilst the latter is known as an X hole. Classes of fit in the British Standard system are broadly

TABLE III

Classes of Fit with Unilateral Holes

Designation	Type of Fit	Class of Fit
UF	Heavy Drive	Interference
UE	Light Drive	
UD	Heavy Keying	Transition
UC	Medium Keying	
UB	Light Keying	
UK	Push	
UL	Slide or Easy Push	Clearance
UP	Easy Slide or Close Running	
UM	Close Running (1)	
UQ	Close Running (2)	
UR	Normal Running	
US	Slack Running	
UT	Extra Slack Running	
UTT	Coarse Clearance	

divided into Interference, Transition, and Clearance. These three classes are again subdivided, and the grouping depends somewhat upon which system of hole dimension is in use. In the case of unilateral holes we have the list in Table III, whilst in the case of bilateral holes, which are in general somewhat smaller, we have the list in Table IV.

The B.S.I. has recommended that the unilateral system should be applied, wherever possible, to all cylindrical mating surfaces. Holes are divided into various categories, according to the tolerance permitted on their diameter. Thus, with unilateral holes, we have classes *B*, *U*, *V*, and *W*, in which *B* are the most accurate, *U* have twice the tolerance of *B*, *V* twice the tolerance of *U*, and *W* twice the tolerance of *V*. The corresponding letters in the bilateral system are *K*, *X*, *Y*, and *Z*.

British Standard Specification No. 164—1924 (war issue 1941) gives the limits permitted in the above categories of hole for a wide range of sizes, whilst a supplement gives similar limits for metric sizes. Limits for a selection of nominal sizes are given in Table V.

TABLE IV

CLASSES OF FIT WITH BILATERAL HOLES

Designation	Type of Fit	Class of Fit
XF	Force	
XE	Heavy Drive	Interference
XD	Light Drive	
XC	Extra Light Drive	
XB	Heavy Keying	
XK	Medium Keying	Transition
XL	Light Keying	
XP	Push	
XM	Slide or Easy Push	
XQ	Easy Slide or Close Running	
XR	Normal Running	
XS	Slack Running	Clearance
XT	Extra Slack Running	
XTT	Coarse Clearance	

Referring back to Tables III and IV showing classes of fit, it will be apparent that, for a given size of hole, the limits to the size of shaft will depend upon the class of fit for which it has been designed. As we have seen, a shaft which is to be a force fit will have a diameter slightly greater than plan size, whilst one which is to be a running fit

TABLE V*

LIMITS FOR DIFFERENT CATEGORY HOLES

Nominal Size Inches	UNILATERAL HOLES			
	B	*U*	*V*	*W*
0·5	+ 0·0004 0	+ 0·0008 0	+ 0·0016 0	+ 0·0032 0
1·0	+ 0·0006 0	+ 0·0012 0	+ 0·0024 0	+ 0·0048 0
1·5	+ 0·0007 0	+ 0·0014 0	+ 0·0028 0	+ 0·0056 0
2·0	+ 0·0007 0	+ 0·0014 0	+ 0·0028 0	+ 0·0056 0
3·0	+ 0·0009 0	+ 0·0018 0	+ 0·0036 0	+ 0·0072 0
4·0	+ 0·001 0	+ 0·002 0	+ 0·004 0	+ 0·008 0
	BILATERAL HOLES			
	K	*X*	*Y*	*Z*
0·5	+ 0·0002 – 0·0004	+ 0·0004 – 0·0004	+ 0·0008 – 0·0008	+ 0·0016 – 0·0016
1·0	+ 0·0003 – 0·0003	+ 0·0006 – 0·0006	+ 0·0012 – 0·0012	+ 0·0024 – 0·0024
1·5	+ 0·0003 – 0·0004	+ 0·0007 – 0·0007	+ 0·0014 – 0·0014	+ 0·0028 – 0·0028
2·0	+ 0·0003 – 0·0004	+ 0·0007 – 0·0007	+ 0·0014 – 0·0014	+ 0·0028 – 0·0028
3·0	+ 0·0004 – 0·0005	+ 0·0009 – 0·0009	+ 0·0018 – 0·0018	+ 0·0036 – 0·0036
4·0	+ 0·0005 – 0·0005	+ 0·001 – 0·001	+ 0·002 – 0·002	+ 0·004 – 0·004

* Abstracted from B.S. 164, "Limits and Fits for Engineering," by permission of the British Standards Institution, from whom official copies of the specification may be obtained, price 2s. 3d. post free.

will have a diameter slightly under plan size. In point of fact the limits for a given class of shaft are the same whether the corresponding hole be specified in the unilateral or in the bilateral system. These limits, for the same plan sizes for which we have shown the limits for holes, are given in Table VI, which should be compared with that for holes.

The various values of limits given in the aforementioned tables are, as we have said, extracted from fuller tables given in B.S.S. 164—1924. The various values given in that specification have been based upon

TABLE VI*

LIMITS FOR SHAFTS OF DIFFERENT FITS

Nominal Size In.	F	E	D	C	B	K	L
0·5	+ 0·0016 + 0·0012	+ 0·0012 + 0·0008	+ 0·0008 + 0·0004	+ 0·0006 + 0·0002	+ 0·0004 0	+ 0·0002 − 0·0002	0 − 0·0004
1·0	+ 0·0024 + 0·0018	+ 0·0018 + 0·0012	+ 0·0012 + 0·0006	+ 0·0009 + 0·0003	+ 0·0006 0	+ 0·0003 − 0·0003	0 − 0·0006
1·5	+ 0·0028 + 0·0021	+ 0·0021 + 0·0014	+ 0·0014 + 0·0007	+ 0·001 + 0·0003	+ 0·0007 0	+ 0·0003 − 0·0004	0 − 0·0007
2·0	+ 0·0028 + 0·0021	+ 0·0021 + 0·0014	+ 0·0014 + 0·0007	+ 0·001 + 0·0003	+ 0·0007 0	+ 0·0003 − 0·0004	0 − 0·0007
3·0	+ 0·0036 + 0·0027	+ 0·0027 + 0·0018	+ 0·0018 + 0·0009	+ 0·0013 + 0·0004	+ 0·0009 0	+ 0·0004 − 0·0005	0 − 0·0009
4·0	+ 0·004 + 0·003	+ 0·003 + 0·002	+ 0·002 + 0·001	+ 0·0015 + 0·0005	+ 0·001 0	+ 0·0005 − 0·0005	0 − 0·001
	P	M	Q	R	S	T	TT
0·5	− 0·0002 − 0·0006	− 0·0004 − 0·0008	− 0·0006 − 0·0012	− 0·0012 − 0·002	− 0·002 − 0·0032	− 0·0032 − 0·0048	− 0·0048 − 0·008
1·0	− 0·0003 − 0·0009	− 0·0006 − 0·0012	− 0·0009 − 0 0018	− 0·0018 − 0·003	− 0·003 − 0·0048	− 0·0048 − 0·0072	− 0·0072 − 0·012
1·5	− 0·0004 − 0·0011	− 0·0007 − 0·0014	− 0·0011 − 0·0021	− 0·0021 − 0·0035	− 0·0035 − 0·0056	− 0·0056 − 0·0084	− 0·0084 − 0·014
2·0	− 0·0004 − 0·0011	− 0·0007 − 0·0014	− 0·0011 − 0·0021	− 0·0021 − 0·0035	− 0·0035 − 0·0056	− 0·0056 − 0·0084	− 0·0084 − 0·014
3·0	− 0·0005 − 0·0014	− 0·0009 − 0·0018	− 0·0014 − 0·0027	− 0·0027 − 0·0045	− 0·0045 − 0·0072	− 0·0072 − 0·0108	− 0·0108 − 0·018
4·0	− 0·0005 − 0·0015	− 0·001 − 0·002	− 0·0015 − 0·003	− 0·003 − 0·005	− 0·005 − 0·008	− 0·008 − 0·012	− 0·012 − 0·02

* Abstracted from B.S. 164, "Limits and Fits for Engineering," by permission of the British Standards Institution, from whom official copies of the specification may be obtained, price 2s. 3d. post free.

practical considerations, and have been reached by means of a simple empirical rule. There is a multiplier m which varies with the *size* of the work and a range factor r which varies with the *category* of the hole. The value of any given limit is determined by multiplying r by m. Values of m and r are given in Tables VII and VIII. The results are in multiples of 0·001 in.

FIG. 78. LIMIT PLUG GAUGE

To illustrate the use of these tables consider a category W hole of 2·0 in. diameter with a shaft made to a running fit R. We see that the value of m is 7. The values of r are for the hole + 0·8 and 0, and for the shaft − 0·3 and − 0·5. From these values we see that the limits on

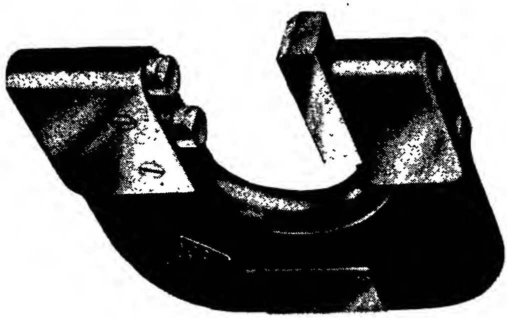


FIG. 79. LIMIT SNAP GAUGE

the size of the hole are, high + 0·0056 in., low 0, whilst those on the size of the shaft are, high − 0·0021 in., low − 0·0035 in. It will be seen that these are, in fact, the values given in the tables.

Limit Gauges. Fig. 78 shows the type of limit gauge normally used for examining internal diameters. One end of the gauge is ground to the low limit of the work (within the appropriate tolerance) whilst the other end is ground to the high limit of the work.

For the inspection of external diameters a type of gauge as illustrated in Fig. 79 is used. These particular gauges are adjustable so that the anvils may be set by means of slip gauges to any desirable value. They may, of course, also be obtained with fixed anvils which,

TABLE VII*

Values of Multiplier m

Nominal Size Inches	m	Nominal Size Inches	m
0 to 0·29	3	3·6 to 4·49	10
0·3 „ 0·59	4	4·5 „ 5·49	11
0·6 „ 0·99	5	5·5 „ 6·59	12
1·0 „ 1·49	6	6·6 „ 7·79	13
1·5 „ 2·09	7	7·8 „ 9·09	14
2·1 „ 2·79	8	9·1 „ 10·49	15
2·8 „ 3·59	9	10·5 „ 11·99	16

TABLE VIII*

Values of Range Factor r for Holes and Shafts

Holes	Range Factor r		Shafts	Range Factor r	
	High Limit	Low Limit		High Limit	Low Limit
B	+ 0·1	0	*F*	+ 0·4	+ 0·3
U	+ 0·2	0	*E*	+ 0·3	+ 0·2
V	+ 0·4	0	*D*	+ 0·2	+ 0·1
W	+ 0·8	0	*C*	+ 0·15	+ 0·05
K	+ 0·05	– 0·05	*B*	+ 0·1	0
X	+ 0·1	– 0·1	*K*	+ 0·05	– 0·05
Y	+ 0·2	– 0·2	*L*	0	– 0·1
Z	+ 0·4	– 0·4	*P*	– 0·05	– 0·15
A	+ 0·4	+ 0·2	*M*	– 0·1	– 0·2
G	+ 0·6	+ 0·4	*Q*	– 0·15	– 0·3
H	+ 0·8	+ 0·6	*R*	– 0·3	– 0·5
			S	– 0·5	– 0·8
			T	– 0·8	– 1·2
			TT	– 1·2	– 2·0

* Abstracted from B.S. 164, "Limits and Fits for Engineering," by permission of the British Standards Institution, from whom official copies of the specification may be obtained, price 2s. 3d. post free.

while free from the fear of getting out of adjustment, cannot be adjusted to compensate for wear. Such gauges are supplied in almost any required size, and Fig. 80 shows the type used above, about 6 in. diameter up to as much as 48 in.

Great care should be exercised in the use of plug, ring, and gap gauges (as indeed with all delicate instruments). It is important to

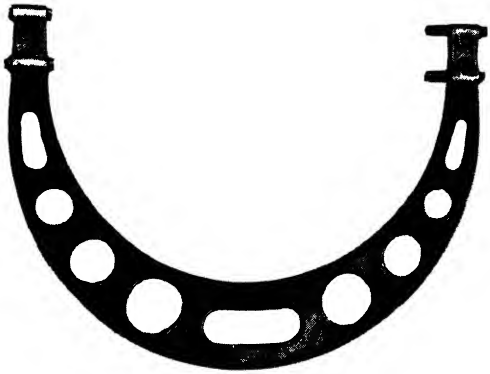


FIG. 80. LIMIT SNAP GAUGE

avoid any force in applying the gauge to the work, and application should be made as "squarely" as possible.

Gauge Limits. In Chapter V we discussed some of the principles underlying the relationship between workshop and inspection gauges, and saw a few examples of the limits of size permitted in certain specific cases of gap gauge. We give in Tables IX and X more complete lists of sizes for gauges for both internal and external diameters. These values have been taken from the War Emergency British Standard Specification 969—1941, issued by the British Standards Institution.

It will be clear, especially if reference is made to Fig. 10 in Chapter V, that, in regard to *holes*, the limits for "go" gauges should be disposed about the *Low* limit for the hole whilst those for the "not go" gauges should be disposed about the *High* limit for the hole.

Conversely, in regard to *shafts*, the limits for the "go" gauges should be disposed about the *high* limit for the shaft whilst those for the "not go" gauges should be disposed about the *Low* limit for the shaft.

We can now consider the use of the foregoing tables for determining the limits to be imposed upon the various gauges which will be employed.

TABLE IX*

LIMITS FOR PLUG GAUGES (INCH UNITS)

Work Tolerance	Gauge Tolerance	Limits "Go" Gauge		Limits "Not Go" Gauge	
		Workshop	Inspection	Workshop	Inspection
0·0005	0·00005	+ 0·00005 0	0 − 0·00005	+ 0·00005 0	+ 0·00005 0
0·001	0·0001	+ 0·0001 0	0 − 0·0001	+ 0·00005 − 0·00005	+ 0·0001 0
0·002	0·0002	+ 0·0002 0	0 − 0·0002	0 − 0·0002	+ 0·0002 0
0·003	0·0003	+ 0·0003 0	0 − 0·0003	0 − 0·0003	+ 0·0003 0
0·006	0·0005	+ 0·0007 + 0·0002	0 − 0·0005	0 − 0·0005	+ 0·0005 0
0·008	0·0006	+ 0·0009 + 0·0003	0 − 0·0006	− 0·0001 − 0·0007	+ 0·0006 0
0·01	0·0007	+ 0·0011 + 0·0004	0 − 0·0007	− 0·0001 − 0·0008	+ 0·0007 0
0·02	0·0012	+ 0·0019 + 0·0007	0 − 0·0012	− 0·0002 − 0·0014	+ 0·0012 0
0·05	0·004	+ 0·005 + 0·001	0 − 0·004	− 0·0005 − 0·0045	+ 0·004 0
0·1	0·006	+ 0·008 + 0·002	0 − 0·006	− 0·001 − 0·007	+ 0·006 0

Suppose it is desired to specify the gauges required in the case of a category *W* hole of 2·5 in. plan diameter and a shaft with a running fit *R*.

Reference to the appropriate tables shows that

$$m = 8$$

$$r\text{ (Hole)} = \begin{cases}\text{High} + 0{\cdot}8\\ \text{Low} \quad 0\end{cases}$$

$$r\text{ (Shaft)} = \begin{cases}\text{High} - 0{\cdot}3\\ \text{Low} - 0{\cdot}5\end{cases}$$

* Abstracted from B.S. 969, "Tolerances for Plain Limit Gauges," by permission of the British Standards Institution, from whom official copies of the specification may be obtained, price 2s. 3d. post free.

TABLE X*

LIMITS FOR RING AND GAP GAUGES (INCH UNITS)

Work Tolerance	Gauge Tolerance	Limits "Go" Gauge		Limits "Not Go" Gauge	
		Workshop	Inpsection	Workshop	Inspection
0·0005	0·00005	0 – 0·00005	+ 0·00005 0	0 – 0·00005	0 – 0·00005
0·001	0·0001	0 – 0·0001	+ 0·0001 0	+ 0·00005 – 0·00005	0 – 0·0001
0·002	0·0002	0 – 0·0002	+ 0·0002 0	+ 0·0002 0	0 – 0·0002
0·003	0·0003	0 – 0·0003	+ 0·0003 0	+ 0·0003 0	0 – 0·0003
0·006	0·0005	– 0·0002 – 0·0007	+ 0·0005 0	+ 0·0005 0	0 – 0·0005
0·008	0·0006	– 0·0003 – 0·0009	+ 0·0006 0	+ 0·0007 + 0·0001	0 – 0·0006
0·01	0·0007	– 0·0004 – 0·0011	+ 0·0007 0	+ 0·0008 + 0·0001	0 – 0·0007
0·02	0·0012	– 0·0007 – 0·0019	+ 0·0012 0	+ 0·0014 + 0·0002	0 – 0·0012
0·05	0·004	– 0·001 – 0·005	+ 0·004 0	+ 0·0045 + 0·0005	0 – 0·004
0·1	0·006	– 0·002 – 0·008	+ 0·006 0	+ 0·007 + 0·001	0 – 0·006

This gives us the following limits—

$$\text{Hole} = \begin{cases} \text{High} & +\ 0{\cdot}0064 \text{ in.} \\ \text{Low} & 0 \end{cases}$$

$$\text{Shaft} = \begin{cases} \text{High} & -\ 0{\cdot}0024 \text{ in.} \\ \text{Low} & -\ 0{\cdot}0040 \text{ in.} \end{cases}$$

The tolerances are thus—

Hole 0·0064 in.

Shaft 0·0016 in.

* Abstracted from B.S. 969, "Tolerances for Plain Limit Gauges," by permission of the British Standards Institution, from whom official copies of the specification may be obtained, price 2s. 3d. post free.

Referring to the tables giving limits for gauges we find—

Plug gauge (taking values for a work tolerance of 0·006)

$$\text{“Go” workshop gauge} \begin{cases} \text{High} & +\,0{\cdot}0007 \\ \text{Low} & +\,0{\cdot}0002 \end{cases}$$

$$\text{“Go” inspection gauge} \begin{cases} \text{High} & 0 \\ \text{Low} & -\,0{\cdot}0005 \end{cases}$$

The limits of the hole are

$$\begin{cases} \text{High} & 2{\cdot}5064 \\ \text{Low} & 2{\cdot}5 \end{cases}$$

so that the limits of the "go" gauges are

$$\text{Workshop} \begin{cases} \text{High} & 2{\cdot}5007 \text{ in.} \\ \text{Low} & 2{\cdot}5002 \text{ in.} \end{cases}$$

$$\text{Inspection} \begin{cases} \text{High} & 2{\cdot}5 \text{ in.} \\ \text{Low} & 2{\cdot}4995 \text{ in.} \end{cases}$$

It will be noted that, taking an extreme case where the workshop gauge is on its low limit and the inspection gauge on its high limit, any work into which the workshop gauge can just enter will present a clearance of 0·0002 in. to the inspection gauge.

A similar process will determine for us the dimensions of the "not go" gauges. These will be found to be as follows—

$$\text{Workshop} \begin{cases} \text{High} & 2{\cdot}5064 \\ \text{Low} & 2{\cdot}5059 \end{cases}$$

$$\text{Inspection} \begin{cases} \text{High} & 2{\cdot}5071 \\ \text{Low} & 2{\cdot}5064 \end{cases}$$

Values for the ring or gap gauges for the *shaft* will be found to be as follows—

$$\text{“Go” gauges} \begin{cases} \text{Workshop} \begin{cases} \text{High} & 2{\cdot}4976 \\ \text{Low} & 2{\cdot}49745 \end{cases} \\ \text{Inspection} \begin{cases} \text{High} & 2{\cdot}49775 \\ \text{Low} & 2{\cdot}4976 \end{cases} \end{cases}$$

$$\text{“Not go” gauges} \begin{cases} \text{Workshop} \begin{cases} \text{High} & 2{\cdot}49615 \\ \text{Low} & 2{\cdot}4960 \end{cases} \\ \text{Inspection} \begin{cases} \text{High} & 2{\cdot}4960 \\ \text{Low} & 2{\cdot}49585 \end{cases} \end{cases}$$

Diameter Measuring Machines. Where it is desired, for purposes of check or standardization, to make an accurate determination of an internal or external diameter use may be made of a comparator of the vertical or horizontal type in conjunction with suitable slip gauges, as described in Chapter VI.

A direct measurement of external diameter is possible on a diameter measuring machine. Such machines are produced by various manu-

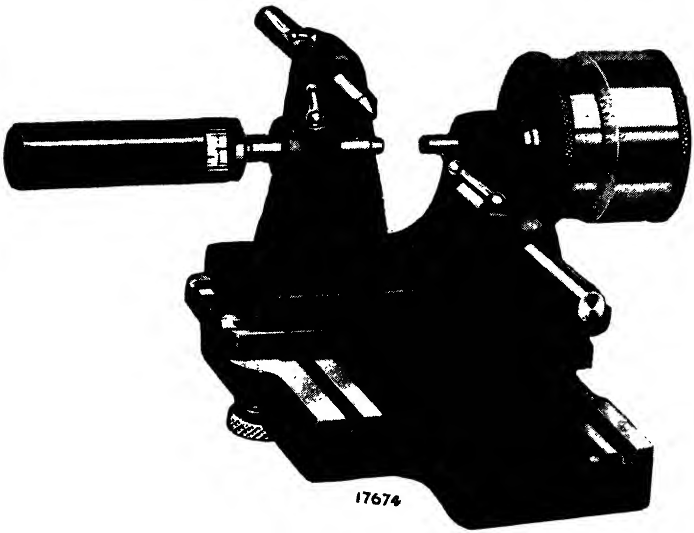


FIG. 81. DIAMETER MEASURING MACHINE

facturers, and a typical example, made by the Pitter Gauge & Precision Tool Co., is shown in Fig. 81.

The machine consists essentially of three portions: a base, an intermediate slide, and a top carriage.

At the ends of the base there are two brackets carrying the centres between which the work is supported. There are two longitudinal grooves on the top of the base.

The under portion of the intermediate slide is fitted with cone studs and a roller which permit it to be moved at will along the longitudinal grooves in the base. On the top of the intermediate slide there are ground two V grooves.

The top carriage is fitted on either side with two brackets which carry respectively a micrometer and a fiducial indicator. It is mounted on three steel balls, two of which fit into one of the upper grooves of

the intermediate slide and one into the other. This provides an easy geometrical support, and the top carriage is thus quite free to move in a lateral manner so as to take up its natural position when a measurement is being made. Fig. 82 shows a close view of the instrument being used for measuring the pitch diameter of a screw plug by aid of thread measuring wires or cylinders. (See Chapter X.)

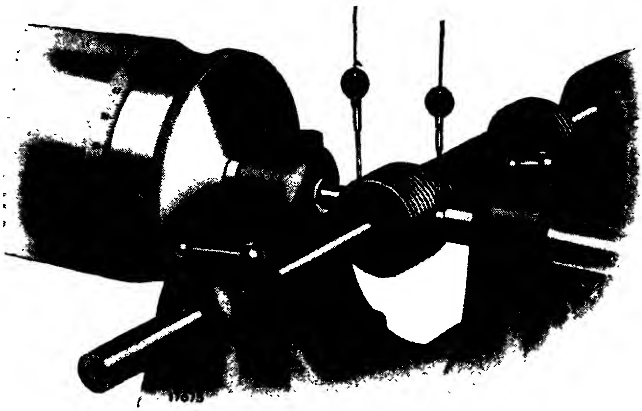


Fig. 82. Diameter Measuring Machine (Close View)

The micrometer is graduated in divisions of 0·0001 in., and estimations can be made to the nearest 0·00002 in. The fiducial anvil has a magnification of 250 to the indicator, and by this means an experienced operator should be able to detect movement or repeat readings to within 0·00005 in.

The machine lends itself very readily to use as a comparator. When it is desired to make direct measurements it is advisable to calibrate by using a slip gauge or, preferably, a reference cylinder of approximately the same diameter as that of the work to be tested. Reference cylinders are obtainable with accuracy guaranteed to the nearest 0·00001 in.

CHAPTER IX

MEASURING ANGLES

Protractor. Where it is required to measure an angle such, for example, as that presented by a plan view of a piece of work, an ordinary protractor is suitable providing that not a very high degree of accuracy is required. For highly accurate work use should, if possible, be made of a toolmaker's microscope with angle attachment. (See Chapter VI.)

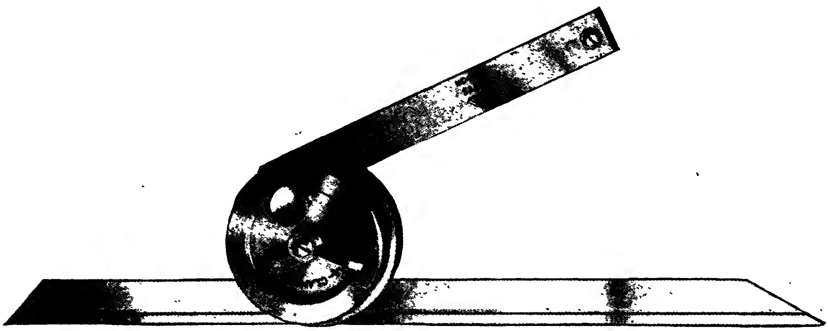


FIG. 83. OPTICAL BEVEL PROTRACTOR

Optical Bevel Protractor. It is often necessary to measure the angle between two members or faces of a mechanism. For this purpose an adjustable protractor may be used. In such an instrument its two members may be set to the angle of the work by laying them against it and the angle between them is then read from a circular scale engraved in degrees forming part of the instrument.

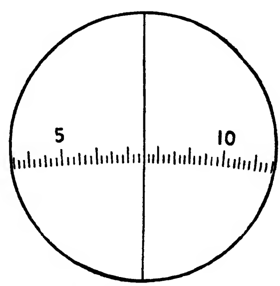


FIG. 84. OPTICAL PROTRACTOR (FIELD OF VIEW)

Fig. 83 shows a more accurate instrument of this type produced by Messrs. E. R. Watts & Son. In this instrument the angular displacement between the two members is observed by means of a microscope eye-piece reading an accurately divided glass annulus mounted within the head. Fig. 84 shows the field of view. The long blade is 12 in. in length and the short blade 6 in. Readings can be made to within 2 to 3 minutes of arc.

Fig. 85 illustrates a variety of uses for such an instrument.

Use of Angle Gauges. These gauges were described in Chapter V. They are normally used for determining the angle through which work has been rotated. For this purpose the work should be mounted between centres and some arrangement provided to enable the gauges to be mounted, rotated with the work and viewed through some form

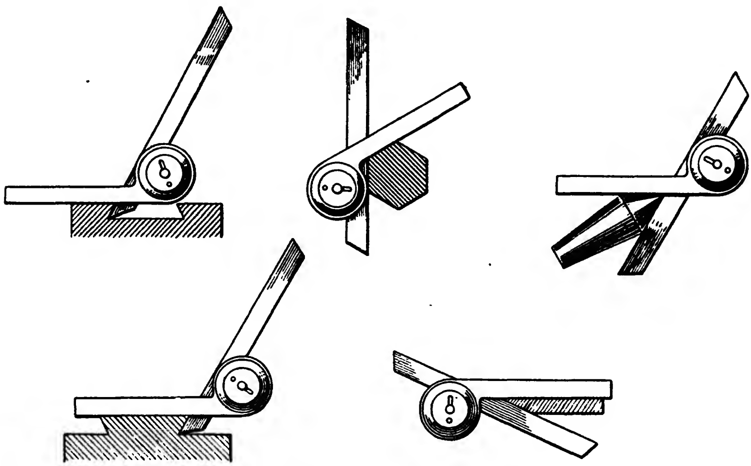


FIG. 85. BEVEL PROTRACTOR USES

of collimator combination, preferably an auto-collimator. Alternatively a sensitive spirit level may be used.

Fig. 86 shows a suitable form of bench made by the Coventry Gauge & Tool Co. The work is mounted on the face plate in its datum position and the spindle locked. The precision square, which will have been located behind the face plate where it can be seen in the illustration, is adjusted until one face either gives zero indication on the auto-collimator or else is as nearly as possible horizontal as indicated by a sensitive spirit level, say one giving a deflection of one division for an angle of tilt of 6 seconds of arc. The square is then locked, by means of a knurled ring, to the face plate in this position. A combination of gauges to give the desired angle is then wrung on to the face of the precision square so that, by unlocking and rotating the spindle, we may readily determine, by means either of the auto-collimator or the spirit level, when rotation has taken place through the desired angle.

It is sometimes desired to check the angle of rotation of some

instrument, as indicated by *itself*, against the true angle as indicated by angle gauges. In such a case the same procedure as above is followed except that the square and gauges must be mounted on the rotating portion of the work and the reading of the work recorded against that given by the gauges.

Divided Circles. These circles are essential features of many angle measuring instruments. Owing to its low temperature coefficient and general refractory nature glass is usually employed for the material

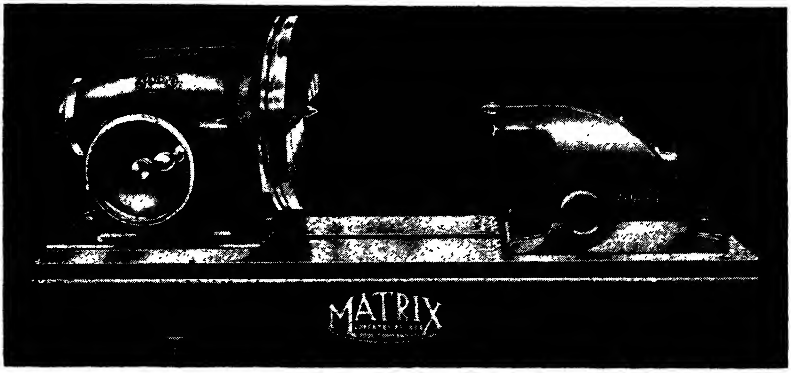


FIG. 86. ANGLE GAUGE HEAD

to be engraved. Owing to their wide application it might be of interest to consult the article on "Graduation" in the *Encyclopædia Britannica* or that on "Divided Circles" in the *Dictionary of Applied Physics* for a great deal of valuable information in this connection.

Two main types of error can arise in the use of circles. One of these is due to the fact that, although all the graduations may have been correctly made, the circle itself has been incorrectly mounted. The other is due to imperfections in the actual graduations of the circle.

Eccentricity. In Fig. 87 suppose the circle to represent a circular scale of some kind (as, for example, a divided circle) which we will suppose to have been correctly engraved in degrees with C as the centre. It clearly makes no difference to our considerations whether we suppose the pointer to be fixed and the circle to rotate or the circle to be fixed and the pointer to rotate. Let us suppose, then, that the pointer P rotates about a centre C' which is eccentric by the amount CC' to C. In its four 90-degree positions the pointer will be as shown at P_0, P_1, P_2, and P_3. The true position for the pointer, if its

pivot had been concentric with C, would have been as indicated by the arrows. We see that the actual *reading* at position P_1 is *greater* than 90° by the length CC', that at P_2 is truly 180°, whilst that at P_3 is *less* than 270°. That is to say that the *error* rises from zero at 0° to a maximum at 90°, falls to zero at 180°, rises to a negative maximum at 270°, and falls to zero at 360°. It can be shown that, for reasonably small eccentricity, the error, if plotted against the reading, will lie on a sine curve. In practice, this means that if we find the curve representing error to be more or less a sine curve we know that there is eccentricity along the diameter joining the points of zero (or minimum) error. In the case of a dial or circle of 6 in. diameter, an eccentricity of 0·001 in. will cause maximum errors of approximately 1 minute of arc.

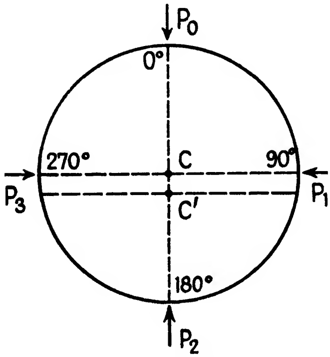


Fig. 87. Effect of Eccentricity

Graduation Errors. In actual fact the curve of errors will not, in general, be a true sine curve, and it then becomes necessary to use what may be called the "mean" sine curve to determine the eccentricity. Any departures from this "mean" sine curve will then be errors due to other causes, the most likely of which will be errors of graduation, which may then be plotted.

Use of Two Pointers. It can be shown that if we employ two pointers (or microscopes) at opposite ends of a diameter and take the mean of their readings (after making the correction necessitated by the fact that one is displaced 180° from the other), the errors due to eccentricity cancel out. In Fig. 87 it can be seen, for example, that the plus error at P_1 cancels the minus error at P_3.

It is possible, indeed probable, that the two pointers, or microscopes, will not be exactly 180° apart. Providing that the departure from 180° is not great, as it need not be, and providing that we take as zero that point at which the *average* of the two readings (as above defined) is zero, it still remains true that eccentricity errors are cancelled at any point by taking the mean of the two readings.

Additional Errors. In a well-made instrument, errors due to further causes should be very small indeed. If the pivot is not truly circular there will be further periodic errors, the frequency of repetition

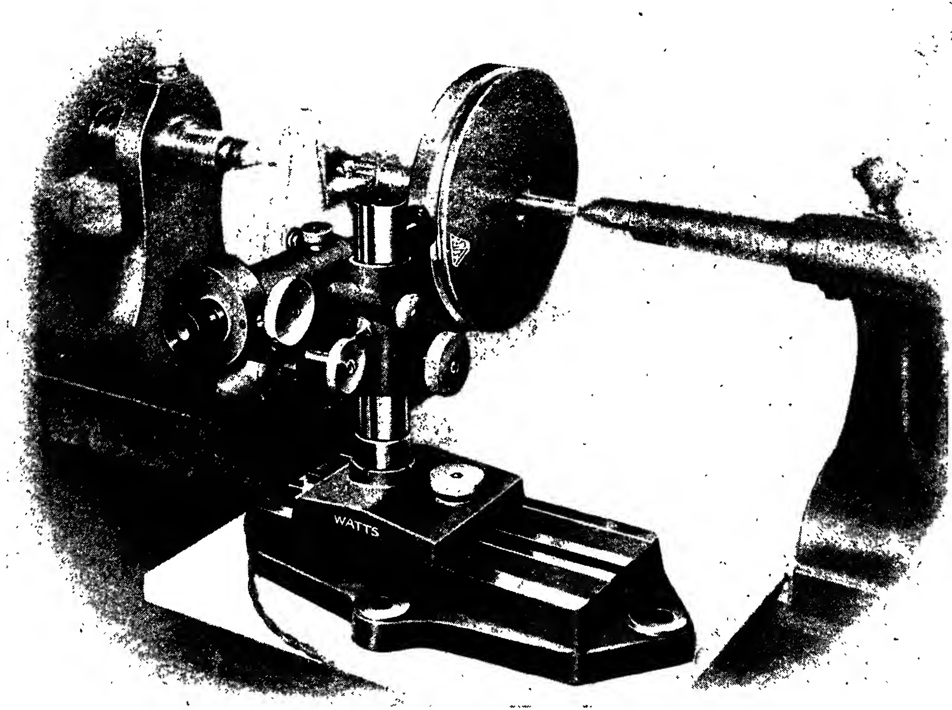


Fig. 88 Circle Division Tester

depending upon the type of departure from circularity. An elliptical pivot, for example, will give errors which repeat twice per revolution. An imperfectly fitted pivot, i.e. one in which there is actual "play," will give rise to inconsistency of readings.

Circular Division Tester. Fig. 88 shows an instrument produced by Messrs. E. R. Watts & Son. With this it is possible to make direct measurement of the angular rotation of work under observation, such as gears, cams, splined shafts, etc. It consists of two main units, the Master Circle Unit and the Microscope Unit. The former carries a silver scale engraved around the periphery and adjacent to it there is a groove against which a precision clock indicator is held to ensure concentricity during rotation. The circle may be adjusted to be truly concentric with the shaft or arbor by means of some radial adjusting screws which are provided for the purpose.

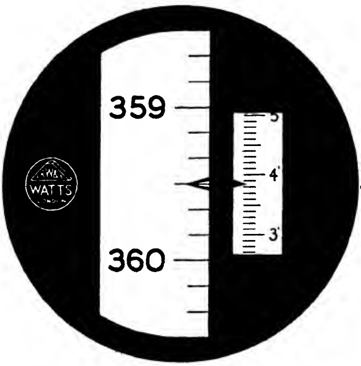


FIG. 89. CIRCLE TESTER (FIELD OF VIEW)

The microscope unit includes a substantial base and pillar for mounting the microscope. Rack and pinion motions are provided to facilitate setting and focusing in relation to the engraved circle. The scale is illuminated and its divisions of degrees and $\frac{1}{6}$ degree (10 minutes) are clearly seen. In addition to this there is, within the field of view, a subsidiary scale by means of which any one 10-minute interval is subdivided into divisions of 0·1 minute so that readings may be made by estimation to the nearest, say, 0·02 minute. (See Fig. 89.)

The accuracy of the instrument depends mainly upon the centring of the Master Circle, which is $7\frac{1}{4}$ in. in diameter, so that an eccentricity of 0·00015 in. can cause errors up to 10 seconds of arc, since only one microscope is used. Additional errors can be caused, naturally, by any actual errors of engraving and also by any deformation of the circle (such as a tendency to take an elliptical form) after engraving due, perhaps, to fixing. Such errors, however, will probably not exceed 2 seconds.

It is understood that the manufacturers are developing an improved model using, instead of the silver scale engraved on the periphery, a

glass circle with the divisions on its side. There will be, in addition, a circular line for use in centring so that the dial indicator will not be required.

The manufacturers are also developing a very high precision tester using microscopes reading on opposite sides.

Setting a Pivot by Spirit Level. A problem which is frequently met is to set a pivot truly vertical by aid of a spirit level.

The level, provided with elevation adjusting screws at its ends, is suitably mounted on the rotating portion of the apparatus whose pivot requires to be adjusted. The level is then adjusted until its bubble is central. In order to make it so, we are, in fact, setting it so that it is not at right angles to the pivot. The departure from a right angle is clearly equal to the angle of pivot tilt.

The rotating portion of the apparatus is now turned through 180°. As the pivot is not vertical, the bubble will not now be central. It can be seen by simple geometry that the angle of departure from horizontal will be *twice* that of the pivot tilt. The correcting adjustment is, therefore, to apply half to the spirit level and half to the pivot and to repeat the test. The process is continued until the bubble remains central throughout the complete rotation.

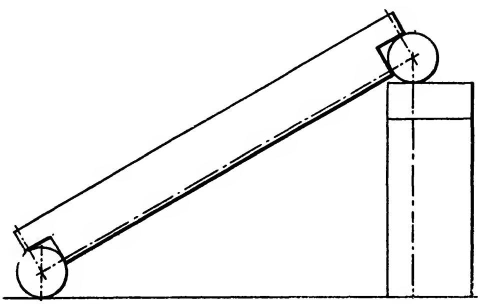


FIG. 90. SINE BAR PRINCIPLE

Sine Bar. In essence this consists of a straight edge of known length one end of which rests upon a true surface whilst the other end is raised by means of slip gauges or the like to a given height. The ratio of this height to the fixed length is the sine of the angle of inclination of the straight edge.

At each end of the straight edge are two gaps which, as shown in Fig. 90, rest upon two cylinders. The lower cylinder rests upon the true surface, whilst the upper one rests on the top of the slip gauges.

It is clear, from a study of the figure, that accuracy will depend upon the following—

1. The truth of the surface used.

2. The equality of the diameters of the two cylinders, although any inequality which might exist could be determined and allowance made for it providing that the cylinders were truly cylindrical.

3. The line through the centres of the cylinders should be parallel

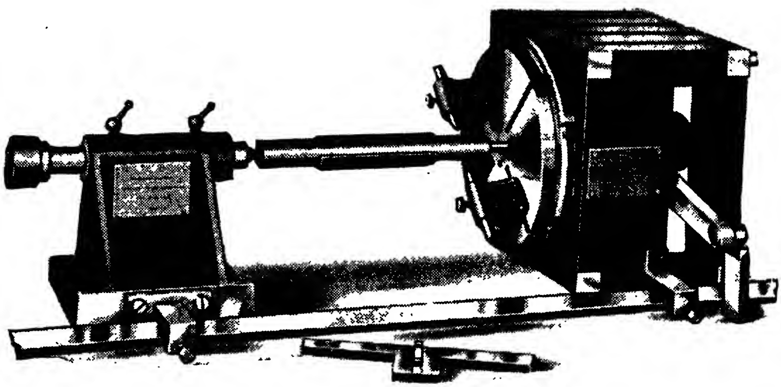


FIG. 91. SINE BAR HEAD

to the working surface of the straight edge or bar, or its departure from parallelism must be determined.

4. The distance between the centres of the cylinders must be known.

Fig. 91 shows an instrument made by the Pitter Gauge & Tool Co. for the measurement of angular rotations and similar movements. The rotating plate is fitted with a ring graduated in degrees. There is a Vernier on the block so that readings may be made to one minute of arc to an accuracy of plus or minus 15 seconds of arc.

Where greater accuracy is required a sine bar is used and provision is made for this behind the rotating plate. There are arrangements whereby the sine bar may be released from or clamped to the rotating plate at will.

There is in addition, as shown, a back centre and straight edge for lining it up with the main block. These are used in the many cases in which the work under test is of such a nature that, as shown in Fig. 91, it requiries to be supported between centres.

The following accuracies are claimed—

Sine bar, 10 in. centres	± 0·0002 in.
Setting plug on sine bar	± 0·00005 in.
Working sides of block, square to one another and to rotating plate	± 0·00025 in.
Face of rotating plate square with axis . .	0·0001 in.
Concentricity of centre peg	0·0001 in.

An elementary use of a sine bar is illustrated in Fig. 92, which indicates a method of checking the angular portion of a gauge. The gauge is clamped to the sine bar, which rests on its rollers, slip gauges, and accurate surface plate. The slip gauges are adjusted until the top edge of the gauge is parallel to the surface plate, as indicated by a sensitive dial gauge or other means. Other similar uses will suggest themselves.

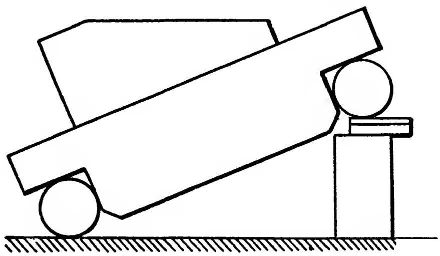


FIG. 92. TEST OF GAUGE ANGLE

Angle by Slip Gauges and Rollers. Fig. 93 indicates a method of using slip and roller gauges for checking the angle in a template gauge. By a knowledge of the difference between the total slips used for height and also that between those used for horizontal distance

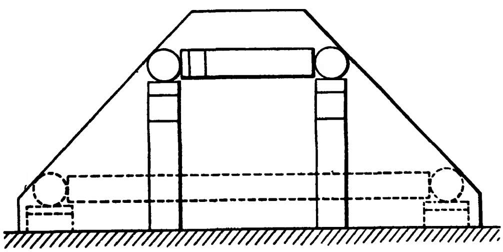


FIG. 93. TEST OF TEMPLATE ANGLE

(which latter will naturally need supports which are not shown in the diagram) it is possible quite simply to determine the angle.

Banks of Collimators. The purpose of these was discussed in Chapter VI. The instrument under test must be provided, if it has not got one, with some form of viewing telescope to be fixed to the rotating portion. There are two methods of procedure. Either the viewing telescope is provided with a single line on its graticule which is brought into coincidence with each collimator image in turn and the error noted on the

dial, or else the graticule of the viewing telescope may be provided with a grid the divisions of which represent, say, minutes or half minutes of arc. The instrument is then rotated to the required reading, as shown on its dial, and the error read on the graticule of the viewing telescope.

When such an arrangement is being used, it is well that, even though there be a periodical test of the angles between adjacent collimators, the test results of any given instrument should be viewed critically. It might, for example, be found that there appeared to be a periodic error in the instrument, which error, however, was in reality due to the fact that one of the collimators had become displaced.

Trains of Gears. In Chapter II we saw that a given instrument could be inspected as a complete whole on a "performance" basis. If satisfactory results are obtained on such overall inspection, it is fair to assume that individual components within the instrument are correct. Thus, if any trains of gears are involved, it is justifiable to assume that these are correct if the overall result is correct. There are, however, one or two points which should be borne in mind.

It might be that the gear ratio is such that, on a repetition of a given reading, all members of the gear train do not have the same teeth as before in engagement. In such a case it would be essential that any series of readings should be taken as many times as there are possible arrangements of gear mesh. Fortunately, in practice it is rare indeed that ratios are such that more than two, or possibly three combinations are possible for any given reading. More usually at a given reading the gears always have the same teeth in mesh. As an example we may imagine an instrument, which has to rotate through 360°, having between the final drive and the indicating dial a gear train with a $4\frac{1}{2}$ to 1 ratio. In such a case it is clear that, on completing one revolution of 360° in the final drive, the high-speed gear wheel (or worm if it should be a worm drive) will be half a revolution away from the point at which it started. Only by taking a *second* set of readings as a continuation of the first could a complete record be obtained.

Following on from the preceding considerations we see that the choice of the actual points at which readings are taken should have reference to the various positions, in regard to mesh, which will be occupied by the different gear wheels or worms in the train.

Where it is desired to make tests on individual gear wheels or worms there is a number of instruments available for the purpose.

Gear Testers. These machines are obtainable in a very wide range

of sizes. There are models suitable for spur or parallel helical gears, bevel and worm gears. In essence they consist of two arbors which carry respectively the gear under test and the one with which it mates during the test. This latter should, preferably, be a master gear, or the equivalent. The one arbor may be clamped in any suitable position, adjusted so that the gears are just meshing correctly. The other arbor is held under the action of a spring so that mesh is maintained

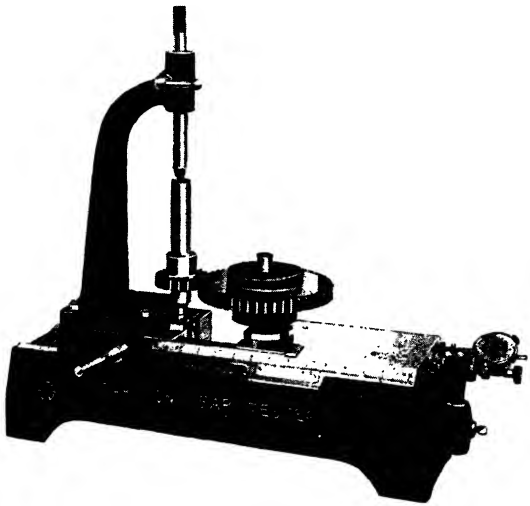


FIG. 94. SPUR GEAR TESTER

and the gears are then rolled together. Movement of the second arbor is indicated on a dial indicator, or, alternatively, a circular disc recorder may be fitted. Errors due to thick teeth, bad tooth form, etc., are readily observed.

Fig. 94 shows a machine suitable for testing gears held between centres. This particular size can accept gears from $1\frac{1}{2}$ in. to 9 in. between centres.

Fig. 95 shows a similar machine, but with attachment for testing bevel gears up to a size of $5\frac{1}{2}$ in. from pitch cone centre to boss.

Fig. 96 shows a similar machine, but with attachment for testing worms and worm wheels up to a maximum worm diameter of $4\frac{1}{2}$ in.

The above machines are made by Messrs. J. Parkinson & Son, of Shipley.

Fig. 97 shows a machine made by Messrs. David Brown & Sons, of Huddersfield. Its purpose is to test worms, and by means of it

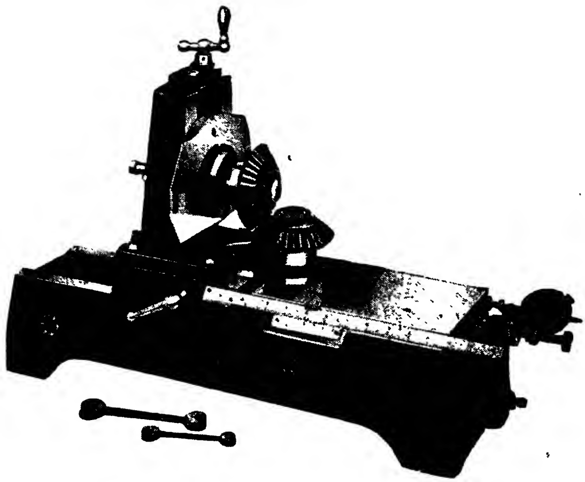


FIG. 95. BEVEL GEAR TESTER

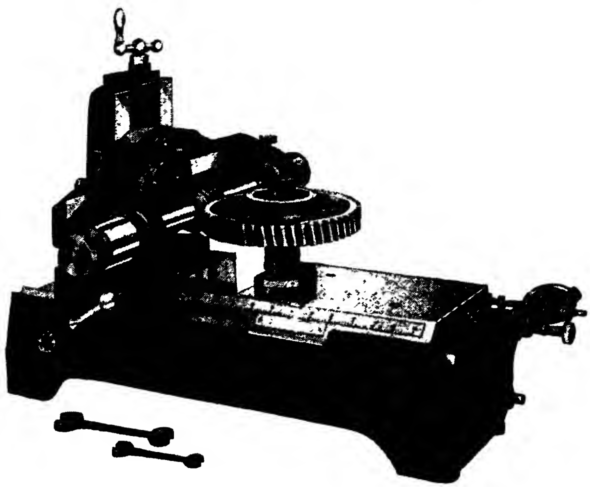


FIG. 96. WORM WHEEL TESTER

measurements may be made of concentricity, thread thickness, pressure angle, or profile and pitch. Measurements are made by aid of suitable feelers and a clock indicator.

This firm also makes a somewhat more elaborate machine of the same type for testing worms and worm wheels in conjunction with one another.

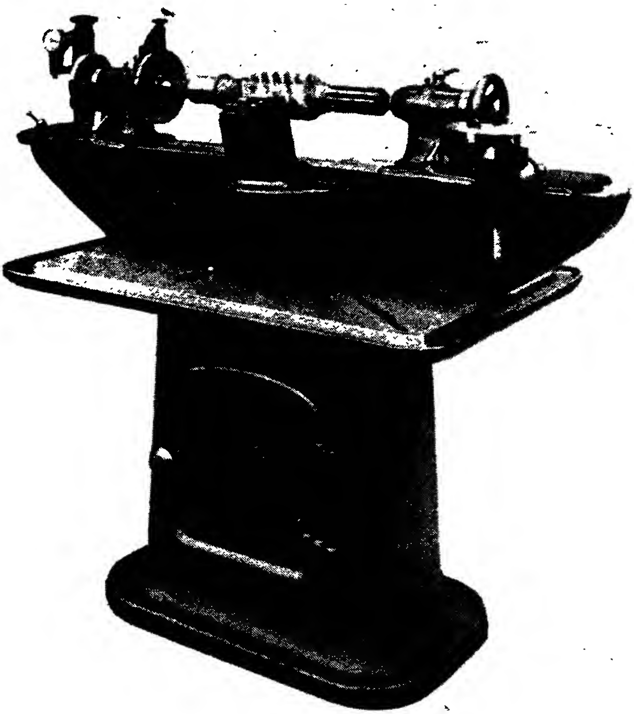


FIG. 97. WORM TEST MACHINE

Gear Tooth Callipers. Fig. 98 shows (in use) an instrument made by Messrs. David Brown & Sons which enables measurements to be made all over a spur tooth profile. There are two adjustments, one for determining the *depth* at which the measurement is to be made, and the other for determining the tooth *width* at that depth. Vernier scales permit readings to 0·001 in. The range covered by these particular instruments is from 0 to 2 in. chord and from 0 to 1 in. depth. Whilst they permit of the fairly exact determination of tooth *shape*, they do not measure tooth *pitch* except indirectly.

The same firm has developed a simplified type, as illustrated in Fig. 99. The prototype was used for some time on actual production work and is preferred by the operatives.

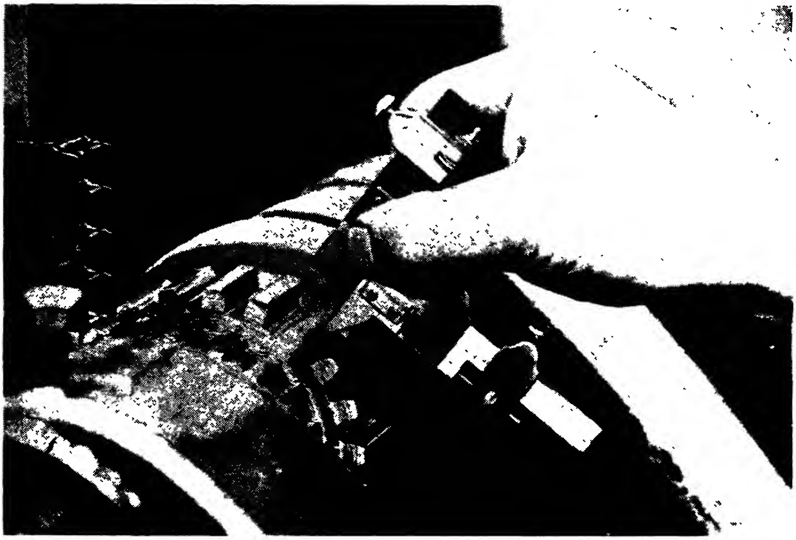


Fig. 98. Gear Tooth Callipers

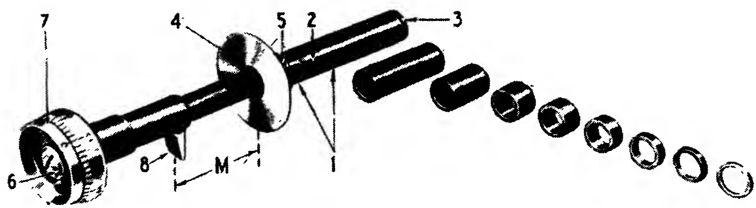


Fig. 99. Gear Tooth Tester

In addition to simplicity in manufacture, this instrument has the advantage of only requiring setting to the linear dimension between the fixed and moving anvils. Measurements are over a number of teeth, as shown in Fig. 100, and as the anvils are tangent to the tooth flanks a definite "feel" is obtained, as in using a micrometer on a cylindrical object, no height measurement being involved.

A range of setting tubes is supplied, each lapped to its precise

length, and the head is in the form of a micrometer dial graduated in thousandths of an inch. The Vernier can therefore be used with equal facility either as a means of initial measurement or as a comparator.

To set the gauge for a distance M in. beween the anvils, appropriate setting tubes are chosen and assembled on the bar 2, the end screw 3 is inserted and tightened, the fixed anvil 4 is moved as close as possible to 3, and the grub screw 5 tightened.

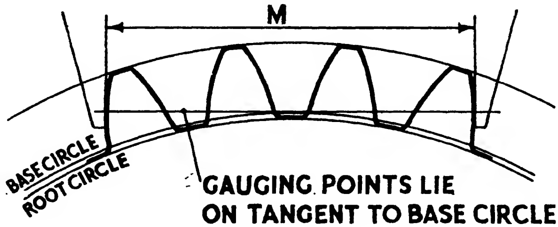


FIG. 100. GEAR TOOTH TESTER (PRINCIPLE)

The screw 6 is loosened until the dial 7 can be rotated through more than a revolution. Slip gauges of length M are placed between the anvils, and the moving anvil is then rotated so as to clamp them against the fixed anvil. The dial 7 is rotated so that its zero mark coincides with that on the scale of the moving anvil. The screw 6 is then tightened to lock the dial, and the instrument then gives the reading when the distance between the anvil is M.

Let t = number of teeth in the gear.

p_n = normal pitch.

ψ_n = normal pressure angle.

ψ_t = transverse pressure angle.

σ = helix angle.

w = tooth thickness at pitch cylinder.

n = number of teeth between measuring surfaces.

M = distance between measuring surfaces.

The value of n is conveniently found by actual trial when a gear is available, but it may be determined beforehand because it is the nearest whole number to

$$\frac{t\psi_n}{\pi} - \frac{w}{p_n} + 1$$

where ψ_n is expressed in radians.

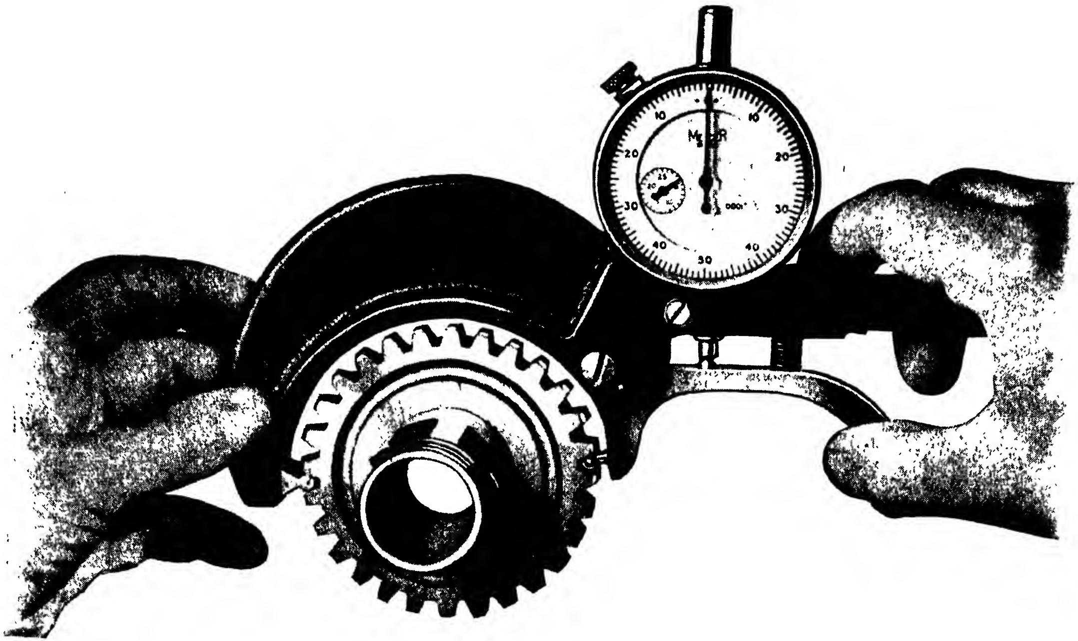


FIG. 101. GEAR PITCH TESTER

If the number of teeth in the gear is large, there may be alternative values of n that can be satisfactorily used.

The distance between the measuring surfaces is given by

$$M = p_n \cos \psi_n \left[\frac{w}{p_n} + (n - l) + \frac{t}{\pi} \operatorname{inv.} \psi_t \right]$$

The angle ψ_t is determined from $\tan \psi_t = \tan \psi_n \sec \sigma$ and $\operatorname{inv.} \psi_t = \tan \psi_t - \psi_t$.

This is best determined from a table of involute functions.

Gear Pitch Comparator. The instrument illustrated in Fig. 101 is manufactured by Messrs. J. E. Baty & Co., and its operation is self-evident. The dial indicator is graduated in 0·0001 in., so that very accurate comparisons of pitch diameter may be made. The same firm also manufactures a similar article but with the anvils spaced slightly differently, so that chordal spacing between a given number of teeth may be rapidly compared with a standard.

Retractable Fiducial Stops. The arrangement shown in Fig. 38 permits very accurate determination of variation in pitch. It is possible to use only one stop in association with a sine bar and slip gauges, or else to use two stops. In the former case the gear wheel is rotated so as to be *just* in contact with the stylus when the latter is biased either upwards or downwards as desired. The stylus is withdrawn and the gear rotated through the correct tooth pitch angle as determined by slip gauges and the sine bar and the stylus brought forward again. It is then once more brought forward and, by means of the micrometer head, it is possible to bring it once more into contact with the gear and the movement of the micrometer head is an accurate indication of the pitch error. In the latter case the left-hand stop (that without a micrometer head) is used for ensuring that the gear is rotated through one tooth pitch and the error determined as before. In this case the indications are the variation in the arc embraced by the number of teeth between the left-hand and the right-hand stops.

Involute Tester. Fig. 102 shows an instrument made by Messrs. David Brown & Sons for testing the form of an involute tooth. The principle of operation is shown in Fig. 103, in which one tooth of a gear and its base circle are shown. When the centre is at A_1 let the circle be in contact with a straight edge at B_1. If now the circle be rolled along the straight edge till its centre is at A_2 and the point of contact with the straight edge is at B_2, a stylus at C in contact with the tooth profile should remain in contact with that profile, without

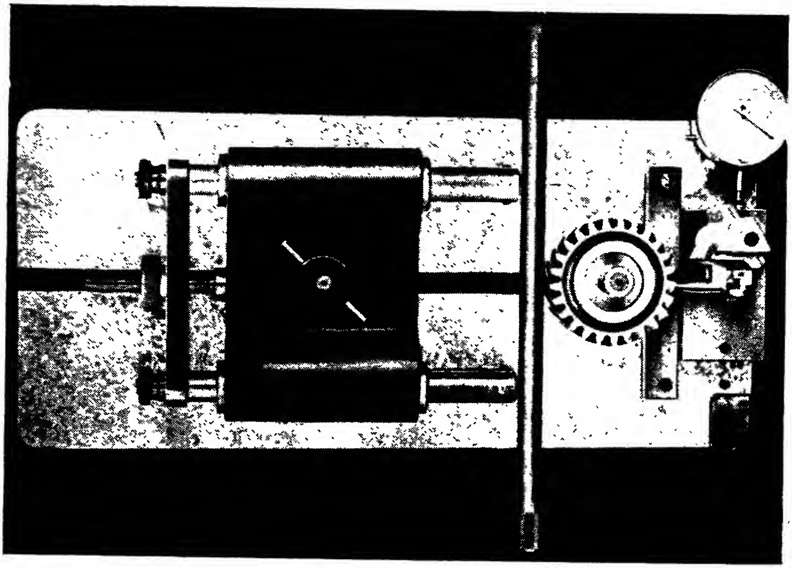


FIG. 102. INVOLUTE TESTER

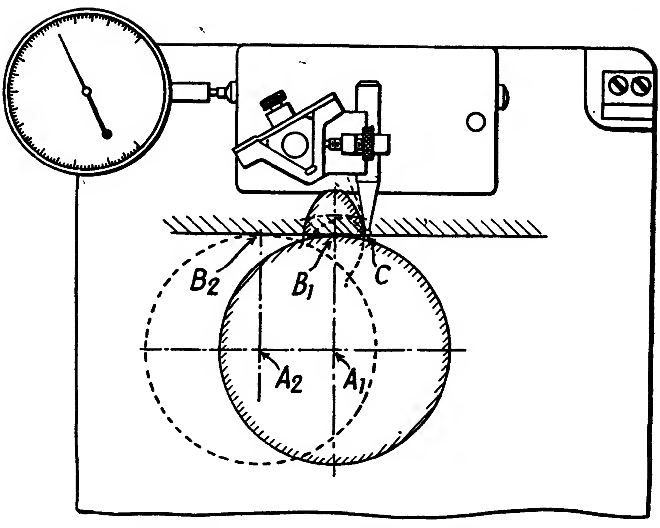


FIG. 103. INVOLUTE TESTER PRINCIPLE

moving, whilst the rolling is taking place. Any movement indicates an error in tooth form. Fig. 104 shows the gear mounted over a disc of diameter equal to that of the base circle. A carriage carrying two spring plungers fitted at their extremities with rollers is clamped so that the spring plungers press the otherwise free transverse rod against the base disc and thus hold its other side against the straight edge. Movement of the transverse rod in either direction will cause the base circle to roll along the straight edge. Movement of the

FIG. 104. INVOLUTE TESTER (CLOSE VIEW)

stylus is communicated by a system of levers to a dial indicator which reads to 0·0001 in.

Useful Gear Formulae. The following symbols are employed in the formulae given—

Diametral pitch	*DP*
Circular pitch	*P*
Number of teeth	*N*
Pitch circle diameter	*D*
Addendum	*A*
Dedendum	*B*
Tooth thickness on pitch circle	*T*
Whole depth of tooth	*W*
Clearance	*F*
Working depth of tooth	*W′*
Outside diameter	*O*
Inside diameter (for internal gears)	*I*
Centre distance	*C*

N.B. Values are normally given in inch units.

The pressure angle normally in use is that of the Brown & Sharpe system, namely 14½°. In the Fellows Stub Tooth gear, which is sometimes used, the pressure angle is 20°.

$$DP = \frac{N}{D} = \frac{\pi}{P}$$

$$T = \frac{P - \text{Backlash}}{2}$$

$$= \frac{1{\cdot}5708}{DP} - \frac{\text{Backlash}}{2}$$

$$F = \frac{0{\cdot}157}{DP}$$

$$W = W' + F$$

$$= \frac{2{\cdot}157}{DP}$$

$$O = \frac{N + 2}{DP}$$

$$I = \frac{N - 2}{DP}$$

$$C = \frac{N_1 + N_2}{2 \times DP} \text{ for } \textit{external} \text{ gears.}$$

$$C = \frac{N_G - N_P}{2 \times DP}$$ for *internal* gears where N_G refers to the gear and N_P to the pinion.

$$*A = \frac{1}{DP}$$

$$*B = \frac{1{\cdot}157}{DP}$$

* N.B. *Although the values given are standard, it should be remembered that departures from these values are not uncommon. The Fellows Stub Tooth uses a false value for DP in these two formulae. This value is usually slightly greater than the true one. Thus a Fellows gear may be said to be* 10/12 *pitch, which means that its true DP is* 10 *but that* 12 *is taken as the value for addendum and dedendum calculations.*

Table XI gives, as illustrations only, a few examples of tooth dimensions for different values of DP, whilst Table XII gives, again

as illustrations only, a few examples of numbers of teeth for different values of *DP* and gear diameter.

TABLE XI

TOOTH DIMENSIONS

DP	*P*	*T*	A_m	*W'*	*W*
4	0·7854	0·3927	0·2500	0·5000	0·5393
6	0·5236	0·2618	0·1666	0·3333	0·3595
8	0·3927	0·1963	0·1250	0·2500	0·2696
10	0·3142	0·1571	0·1000	0·2000	0·2157
12	0·2618	0·1309	0·0833	0·1666	0·1798
14	0·2244	0·1122	0·0714	0·1429	0·1541
16	0·1963	0·0982	0·0625	0·1250	0·1348

TABLE XII

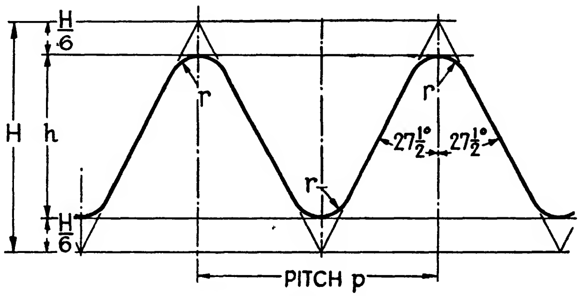
NUMBERS OF TEETH

DP	Pitch Circle Diameters				
	2·5 in.	3 in.	5 in.	10 in.	15 in.
4	10	12	20	40	60
6	15	18	30	60	90
8	20	24	40	80	120
10	25	30	50	100	150
12	30	36	60	120	180
14	35	42	70	140	210
16	40	48	80	160	240

CHAPTER X

MEASURING SCREW THREADS

THE number of varieties of screw threads in use for different purposes is, unfortunately, very great and necessitates a large number of different tools to produce them, and a large number of gauges, etc., to inspect them, if anything like a representative range is to be covered. We shall therefore consider the basic particulars in regard only to the more important types.



H=0·960491xp h=0·640327xp r=0·137329xp

FIG. 105. WHITWORTH THREAD

British Standard Whitworth (B.S. Whit.). This form of thread is the one which is perhaps most commonly used in this country for general purposes. It is also, to some slight extent, used in the United States. Its general particulars are shown in Fig. 105.

This same form of thread is used for British Standard Fine (B.S.F or B.S. Fine), and also for British Standard Pipe (B.S. Pipe).

The main basic particulars for a selection of standard sizes are given in Table XIII.

Fits. There are three grades of fit in the Whitworth Specifications. These are—

Close Fit. This is obtained only by means of the highest quality tools and is specified only for specially refined work.

Medium Fit. This class of fit applies to the better class of interchangeable screw threads.

Free Fit. This applies to the bulk of commercial quality nuts and bolts.

TABLE XIII*

B.S. Screw Threads

Size	Type	Threads per inch	Pitch	Depth of Thread	Root Diameter	Effective Diameter
¼ in.	B.S.W.	20	0·0500	0·0320	0·1860	0·2180
	B.S.F.	26	0·0385	0·0246	0·2008	0·2254
	B.S. Pipe	19	0·0526	0·0337	0·4506	0·4843
½ in.	B.S.W.	12	0·0833	0·0534	0·3932	0·4466
	B.S.F.	16	0·0625	0·0400	0·4200	0·4600
	B.S. Pipe	14	0·0714	0·0457	0·7336	0·7793
¾ in.	B.S.W.	10	0·1000	0·0640	0·6220	0·6860
	B.S.F.	12	0·0833	0·0534	0·6432	0·6966
	B.S. Pipe	14	0·0714	0·0457	0·9496	0·9953
1 in.	B.S.W.	8	0·1250	0·0800	0·8400	0·9200
	B.S.F.	10	0·1000	0·0640	0·8720	0·9360
	B.S. Pipe	11	0·0909	0·0582	1·1926	1·2508
2 in.	B.S.W.	4·5	0·2222	0·1423	1·7154	1·8577
	B.S.F.	7	0·1428	0·0915	1·8170	1·9085
	B.S. Pipe	11	0·0909	0·0582	2·2306	2·2888
3 in.	B.S.W.	3·5	0·2857	0·1830	2·6340	2·8170
	B.S.F.	5	0·2000	0·1281	2·7438	2·8719
	B.S. Pipe	11	0·0909	0·0582	3·3436	3·4018
4 in.	B.S.W.	3	0·3333	0·2134	3·5732	3·7866
	B.S.F.	4·5	0·2222	0·1423	3·7154	3·8577
	B.S. Pipe	11	0·0909	0·0582	4·3340	4·3920

N.B. The sizes given refer to the **internal** diameter in the case of pipes.

Limits. The tolerance which can be permitted in screw threads will depend upon the diameter of the bolt or nut, as also upon the length of engagement. The basic formula upon which *effective* diameter tolerances have been calculated is—

$$0{\cdot}002\sqrt[3]{D} + 0{\cdot}003\sqrt{L} + 0{\cdot}005\sqrt{p}$$

where D = major diameter of thread in inches.

C = length of engagement in inches.

p = pitch in inches.

The values given by this formula apply to a medium fit. They should be decreased by 33⅓ per cent for a close fit and increased by 50 per cent for a free fit.

* Abstracted from B.S. 84, "B.S. Screw Threads of Whitworth Form," by permission of the British Standards Institution, from whom official copies of the specification may be obtained, price 5s. post free.

The tolerance on the *major* diameter of a bolt is greater than that for the effective diameter by an amount equal to $0{\cdot}01\sqrt{p}$.

The tolerance on the *minor* diameter of a bolt is greater than that for the effective diameter by an amount equal to $0{\cdot}013\sqrt{p}$ for close fits and $0{\cdot}02\sqrt{p}$ for medium and free fits.

The tolerances on the diameters of a nut are equal to $0{\cdot}2p$ plus an amount which varies from 0·004 in. for fine threads to 0·007 in. for coarse threads. No tolerance is laid down for the root diameter of a nut.

Tolerances are disposed so that the basic size is the upper limit of a bolt and the lower limit of the nut, except in the case of stainless steel, where there is a tendency to seize, in which case the upper limit for the bolt is 0·001 in. less than the lower limit for the nut. Similar allowances are made in the cases of nuts and bolts which are to be plated. Under the worst possible conditions, viz. a small bolt in a large nut, there will be in engagement a depth of thread which varies from 50 per cent of the full depth for 40 threads per inch to 75 per cent for 4 threads per inch.

Tables XIV and XV show the various plan dimensions and their limits for three grades of fit for a selection of sizes of B.S. Whit. bolts and nuts. The values of tolerance include any effect which may be due to errors in pitch or in flank angle (see page 135). It will be noted that whereas the limits on the root and crest diameters of bolts vary according to the class of fit, those on nuts do not. In both cases, however, the limits on effective diameter (taking into account errors in pitch or flank angle) vary according to the class of fit.

The tables show merely a representative selection of sizes for comparative purposes only. For this reason it has not been considered necessary to include tables of limits for other thread types. For these and for other sizes of B.S. Whit. the reader is referred to the appropriate handbooks.

British Association (B.A.). This type of thread is used for small screws. The shape is generally similar to that of the B.S. Whit., except for the following differences—

Angle between flanks	$47\frac{1}{2}^\circ$.
Radius at crest and root	$\frac{2}{11} \times p$.
Depth of thread	$0{\cdot}6 \times p$.

Metric dimensions are used, and the various sizes are known by numbers (such as 2B.A., 4B.A., etc.). The relationship between the diameter D of a bolt and the thread pitch is—

$$D = 6p^{\frac{6}{5}}$$

TABLE XIV*

Limits on B.S. Whitworth Bolts

Size	Crest Diameter			Effective Diameter			Root Diameter		
	Close	Medium	Free	Close	Medium	Free	Close	Medium	Free
¼ in.	0·2500 + 0 − 0·0048	0·2500 + 0 − 0·0061	0·2500 + 0 − 0·0080	0·2180 + 0 − 0·0026	0·2180 + 0 − 0·0039	0·2180 + 0 − 0·0058	0·1860 + 0 − 0·0055	0·1860 + 0 − 0·0084	0·1860 + 0 − 0·0103
½ in.	0·5000 + 0 − 0·0063	0·5000 + 0 − 0·0081	0·5000 + 0 − 0·0106	0·4466 + 0 − 0·0034	0·4466 + 0 − 0·0052	0·4466 + 0 − 0·0077	0·3932 + 0 − 0·0072	0·3932 + 0 − 0·0110	0·3932 + 0 − 0·0135
¾ in.	0·75000 + 0 − 0·0072	0·7500 + 0 − 0·0092	0·7500 + 0 − 0·0122	0·6860 + 0 − 0·0040	0·6860 + 0 − 0·0060	0·6860 + 0 − 0·0090	0·6220 + 0 − 0·0081	0·6220 + 0 − 0·0123	0·6220 + 0 − 0·0153
1 in.	1·0000 + 0 − 0·0080	1·0000 + 0 − 0·0103	1·0000 + 0 − 0·0137	0·9200 + 0 − 0·0045	0·9200 + 0 − 0·0068	0·9200 + 0 − 0·0102	0·8400 + 0 − 0·0091	0·8400 + 0 − 0·0139	0·8400 + 0 − 0·0173
2 in.	2·0000 + 0 − 0·0108	2·0000 + 0 − 0·0138	2·0000 + 0 − 0·0184	1·8577 + 0 − 0·0061	1·8577 + 0 − 0·0091	1·8577 + 0 − 0·0137	1·7154 + 0 − 0·0122	1·7154 + 0 − 0·0185	1·7154 + 0 − 0·0231
3 in.	3·0000 + 0 − 0·0125	3·0000 + 0 − 0·0161	3·0000 + 0 − 0·0214	2·8170 + 0 − 0·0072	2·8170 + 0 − 0·0108	2·8170 + 0 − 0·0161	2·6340 + 0 − 0·0141	2·6340 + 0 − 0·0215	2·6340 + 0 − 0·0268

* Abstracted from B.S. 84, "B.S. Screw Threads of Whitworth Form," by permission of the British Standards Institution, from whom official copies of the specification may be obtained, price 5s. post free.

TABLE XV*

LIMITS ON B.S. WHITWORTH NUTS

Size	Crest Diameter			Effective Diameter			Root Diameter
	Close	Medium	Free	Close	Medium	Free	
¼ in.	0·1860 + 0·0170 − 0	0·1860 + 0·0170 − 0	0·1860 + 0·0170 − 0	0·2180 + 0·0026 − 0	0·2180 + 0·0039 − 0	0·2180 + 0·0058 − 0	0·2500
½ in.	0·3932 + 0·0237 − 0	0·3932 + 0·0237 − 0	0·3932 + 0·0237 − 0	0·4466 + 0·0034 − 0	0·4466 + 0·0052 − 0	0·4466 + 0·0077 − 0	0·5000
¾ in.	0·6220 + 0·0270 − 0	0·6220 + 0·0270 − 0	0·6220 + 0·0270 − 0	0·6860 + 0·0040 − 0	0·6860 + 0·0060 − 0	0·6860 + 0·0090 − 0	0·7500
1 in.	0·8400 + 0·0320 − 0	0·8400 + 0·0320 − 0	0·8400 + 0·0320 − 0	0·9200 + 0·0045 − 0	0·9200 + 0·0068 − 0	0·9200 + 0·0102 − 0	1·0000
2 in.	1·7154 + 0·0514 − 0	1·7154 + 0·0514 − 0	1·7154 + 0·0514 − 0	1·8577 + 0·0061 − 0	1·8577 + 0·0091 − 0	1·8577 + 0·0137 − 0	2·0000
3 in.	2·6340 + 0·0641 − 0	2·6340 + 0·0641 − 0	2·6340 + 0·0641 − 0	2·8170 + 0·0072 − 0	2·8170 + 0·0108 − 0	2·8170 + 0·0161 − 0	3·0000

The relationship between the pitch and the designating number is—

$$p = (0{\cdot}9)^n$$

so that the relationship between the diameter and the designating number is—

$$D = 6 \times (0{\cdot}9)^{\frac{6n}{5}}$$

Basic dimensions of a range of B.A. sizes are given in Table XVI.

British Standard Cycle (B.S.C.). This type of thread was formerly known as the Cycle Engineers' Institute or C.E.I. thread. Like the B.A. it is generally similar in shape to the B.S. Whit., but differs in the following particulars—

Angle between flanks	60°.
Radius at crest and root	$\frac{1}{6} \times p$.
Depth of thread	$0{\cdot}5327p$.

As its name implies, this type of thread is used in the manufacture of cycles and on certain portions of motor-cycles.

* Abstracted from B.S. 84, "B.S. Screw Threads of Whitworth Form," by permission of the British Standards Institution, from whom official copies of the specification may be obtained, price 5s. post free.

TABLE XVI*

B.A. Screw Threads

Desig-nating Number	Pitch mms.	Pitch inches	Depth of Thread	Crest Diameter mms.	Crest Diameter inches
0	1·00	0·0394	0·60	6·0	0·236
1	0·90	0·0354	0·54	5·3	0·209
2	0·81	0·0319	0·485	4·7	0·185
3	0·73	0·0287	0·44	4·1	0·161
4	0·66	0·0260	0·395	3·6	0·142
5	0·59	0·0232	0·355	3·2	0·126
6	0·53	0·0209	0·32	2·8	0·110
7	0·48	0·0189	0·29	2·5	0·098
8	0·43	0·0169	0·26	2·2	0·087
9	0·39	0·0154	0·235	1·9	0·075
10	0·35	0·0138	0·21	1·7	0·067
11	0·31	0·0122	0·185	1·5	0·059
12	0·28	0·0110	0·17	1·3	0·051

The basic dimensions of a range of sizes of bolts and nuts are given in Table XVII. There are certain other special sizes of this thread, as, for example, crank cotters, steering columns, hub sprockets, etc., which are not listed, but to which reference may be made in appropriate handbooks.

American National Threads. In this thread the truncation at the crest and root of the thread is in the form of a flat and not a radius. The main particulars are as follows—

Angle between flanks	60°.
Breadth of "flat."	$\frac{1}{8} \times p$.
Depth of thread	$0{\cdot}6495p$.

As with the B.S. Whit. threads thère are both coarse and fine types. The basic dimensions of both of these types for a variety of sizes are given in Table XVIII. Reference should be made to the appropriate handbook for other sizes.

* Abstracted from B.S. 93, "British Association Screw Threads," by permission of the British Standards Institution, from whom official copies of the specification may be obtained, price 2s. 3d. post free.

TABLE XVII*

B.S. CYCLE THREADS FOR BOLTS AND NUTS

Size	Threads per inch	Pitch	Depth of Thread	Root Diameter	Effective Diameter
$\frac{1}{8}$	40	0·02500	0·0133	0·0984	0·1117
$\frac{5}{32}$	32	0·03125	0·0166	0·1231	0·1397
$\frac{3}{16}$	32	0·03125	0·0166	0·1543	0·1709
$\frac{7}{32}$	26	0·03846	0·0205	0·1778	0·1983
$\frac{1}{4}$	26	0·03846	0·0205	0·2090	0·2295
$\frac{9}{32}$	26	0·03846	0·0205	0·2403	0·2608
$\frac{5}{16}$	26	0·03846	0·0205	0·2715	0·2920
$\frac{3}{8}$	26	0·03846	0·0205	0·3340	0·3545
$\frac{7}{16}$	26	0·03846	0·0205	0·3965	0·4170
$\frac{1}{2}$	26	0·03846	0·0205	0·4590	0·4795
$\frac{9}{16}$	26	0·03846	0·0205	0·5215	0·5420
$\frac{5}{8}$	26	0·03846	0·0205	0·5840	0·6045
$\frac{11}{16}$	26	0·03846	0·0205	0·6465	0·6670
$\frac{3}{4}$	26	0·03846	0·0205	0·7090	0·7295

There are four classes of fit in the American system as compared with the three classes in the B.S. system. These are as follows—

Class I Fit. This is intended to cover the manufacture of threaded parts where quick and easy assembly is necessary and where an allowance is necessary.

Class II Fit. This is intended to cover the majority of threaded work where interchangeability is required and where no allowance is necessary.

Class III Fit. This is intended to apply to the highest grade of interchangeable screw thread work. It is similar in character to a Class II fit, except that the tolerances are smaller so that production is correspondingly more expensive.

Class IV Fit. This is intended for fine tight fits where a

* Abstracted from B.S. 811, "British Cycle Threads," by permission of the British Standards Institution, from whom official copies of the specification may be obtained, price 2s. 3d. post free.

TABLE XVIII

American National Screw Threads

Size	Type	Threads per inch	Pitch	Depth of Thread	Root Diameter	Effective Diameter
No. 0	Coarse					
0·060 in.	Fine	80	0·01250	0·00812	0·0438	0·0519
No. 1	Coarse	64	0·01562	0·01015	0·0527	0·0629
0·073 in.	Fine	72	0·01389	0·00902	0·0550	0·0640
No. 2	Coarse	56	0·01786	0·01160	0·0628	0·0744
0·086 in.	Fine	64	0·01562	0·01015	0·0657	0·0759
No. 5	Coarse	40	0·02500	0·01624	0·0925	0·1088
0·125 in.	Fine	44	0·02273	0·01476	0·0955	0·1102
No. 8	Coarse	32	0·03125	0·02030	0·1234	0·1437
0·164 in.	Fine	36	0·02778	0·01804	0·1279	0·1460
No. 12	Coarse	24	0·04167	0·02606	0·1619	0·1889
0·216 in.	Fine	28	0·03571	0·02320	0·1696	0·1928
¼ in.	Coarse	20	0·05000	0·03248	0·1850	0·2175
	Fine	28	0·03571	0·02320	0·2036	0·2268
½ in.	Coarse	13	0·07692	0·04996	0·4001	0·4500
	Fine	20	0·05000	0·03248	0·4350	0·4675
¾ in.	Coarse	10	0·10000	0·06495	0·6201	0·6850
	Fine	16	0·06250	0·04059	0·6688	0·7094
1 in.	Coarse	8	0·12500	0·08119	0·8376	0·9188
	Fine	14	0·07143	0·04639	0·9072	0·9536
2 in.	Coarse	4½	0·22222	0·14434	1·7113	1·8557
	Fine					
3 in.	Coarse	4	0·25000	0·16238	2·6752	2·8376
	Fine					
4 in.	Coarse	4	0·25000	0·16238	3·6752	3·8376
	Fine					

N.B. Sizes below ¼ in. are taken from those established by the American Society of Mechanical Engineers (A.S.M.E.).

screw-driver may be necessary in assembly. In production of this class of fit it will be necessary to use precision tools and gauges. In some cases selective assembly may be necessary.

Acme Threads. The form of this thread is shown in Fig. 106. The allowance (C) at the root diameter of the bolt has been indicated as being 0·010 in., but in fact it will usually be less than that for finer

pitches. A similar allowance is provided in the root diameter of nuts to allow clearance between it and the crest of the bolt.

These threads are to be preferred in cases where formerly square

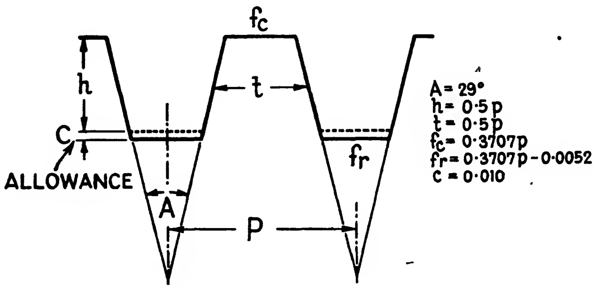


FIG. 106. ACME THREAD

threads would have been used, since it is a much easier problem to machine them. The basic dimensions for a variety of sizes are given in Table XIX.

Metric Screw Threads. These threads are also known as those of the Système International (S.I.). They are the standard threads in use

TABLE XIX*

ACME SCREW THREADS

Size	Threads per inch	Pitch	Depth of Thread (basic)	Root Diameter (basic)	Effective Diameter
¼ in.	16	0·06250	0·03125	0·1875	0·2187
½ in.	10	0·10000	0·05000	0·4000	0·4500
¾ in.	6	0·16667	0·08333	0·5833	0·6667
1 in.	5	0·20000	0·10000	0·8000	0·9000
1½ in.	4	0·25000	0·12500	1·2500	1·3750
2 in.	4	0·25000	0·12500	1·7500	1·8750
3 in.	2	0·50000	0·25000	2·5000	2·7500
4 in.	2	0·50000	0·25000	3·5000	3·7500
5 in.	2	0·50000	0·25000	4·5000	4·7500

* Abstracted from B.S. 1104, "Acme Threads," by permission of the British Standards Institution, from whom official copies of the specification may be obtained, price 2s. 3d. post free.

on the Continent. Their form is the same as that of the American National Thread, and the basic dimensions for a variety of sizes are given in Table XX.

Pitch and Angle Errors. We stated that the limits on effective diameter set out in Tables XIV and XV took into account any errors which might exist in either pitch or flank angle or both.

Pitch. There are four possible types of pitch error—

1. Where the pitch is uniform, but incorrect, the error is said to be "progressive."

2. Where the pitch errors vary from thread to thread but recur at regular intervals the error is said to be "periodic."

3. Where the errors vary over equal fractions of a turn the thread is called "drunken."

4. Where the errors vary in an irregular manner they are said to be "erratic."

TABLE XX*

S.I Screw Threads

Size	Pitch	Depth of Thread	Root Diameter	Effective Diameter
6	1·00	0·650	4·700	5·350
8	1·25	0·812	6·376	7·188
10	1·50	0·974	8·052	9·026
12	1·75	1·137	9·726	10·863
20	2·50	1·624	16·752	18·376
30	3·50	2·273	25·454	27·727
42	4·50	2·923	36·154	39·077
56	5·50	3·572	48·856	52·428
72	6·00	3·897	64·206	68·103
90	6·00	3·897	82·206	86·103
110	6·00	3·897	102·206	106·103
125	6·00	3·897	117·206	121·103

Dimensions in millimetres.

Note. Above 80 mm. diameter sizes increase in steps of 5 mm.

* Abstracted from B.S. 1095, "Metric Screw Threads, Système International," by permission of the British Standards Institution, from whom official copies of the specification may be obtained, price 2s. 3d. post free.

In Fig. 107 suppose the full lines to represent two threads of a bolt, and that the broken lines represent two threads of a nut which engages with it. Suppose further that the thread *forms* are correct, but that there is a pitch error the maximum amount of which (in the length in engagement) is that between the threads shown in the figure. Let this amount be $2a$ displaced uniformly between the two pairs as

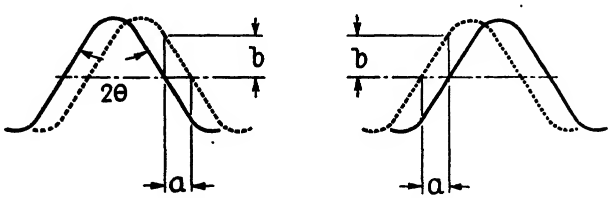


Fig. 107. Pitch Errors

shown. The *radial* error at the pitch cylinder, i.e. the error in effective *radius* which would compensate for this, is clearly b and—

$$b = a \cot \theta$$

TABLE XXI

Effect of Pitch Error on Effective Diameter

Pitch Error	Virtual Difference in Effective Diameter		
	Whitworth	B.A.	B.S.C. U.S.S. S.I.
0·0001	0·00019	0·00023	0·00017
0·0002	0·00038	0·00045	0·00035
0·0003	0·00058	0·00068	0·00052
0·0004	0·00077	0·00091	0·00069
0·0005	0·00096	0·00114	0·00086
0·0006	0·00115	0·00136	0·00104
0·0007	0·00134	0·00159	0·00121
0·0008	0·00154	0·00181	0·00138
0·0009	0·00173	0·00205	0·00156
0·0010	0·00192	0·00227	0·00173

N.B. The error should be "added" for male and "subtracted" for female.

The error in effective *diameter* must be double this, namely—

$$2a \cot \theta$$

Numerical values for $\cot \theta$ for the different standard threads are—

		$Cot\ \theta$
Whitworth	$(2\theta = 55°)$	1·921
B.A.	$(2\theta = 47\frac{1}{2}°)$	2·273
B.S.C. (or C.E.I.) / U.S. Standard / S.I.	$(2\theta = 60°)$	1·732

The values of virtual difference in effective diameter corresponding to various pitch errors are given in Table XXI.

Angle. By drawing diagrams similar to Fig. 107 it is possible to show that errors in flank angle result in a virtual change in effective diameter in accordance with the expression—

$$\frac{l}{\sin 2\theta}(a_1 + a_2)$$

where l = length, in cross-section, of the straight portion of the flank.

$\left.\begin{matrix} a_1 \\ a_2 \end{matrix}\right\}$ = errors in flank angles.

It should be noted that the expression contains the sum of the two angular errors irrespective of their signs. This expression, for the various threads, becomes—

Whitworth	$0{\cdot}0105p\ (a_1 + a_2)$
B.A.	$0{\cdot}0091p\ (a_1 + a_2)$
B.S.C. (or C.E.I.) / U.S. Standard / S.I.	$0{\cdot}0131p\ (a_1 + a_2)$

The errors in angle (a_1 and a_2) are measured in degrees.

The values of virtual difference in effective diameter corresponding to various values for the total $a_1 + a_2$ are given in Tables XXII, XXIII, and XXIV.

Only a selection of sizes have been given. The ranges of errors tabulated have been limited on the one hand by those likely to be met and on the other hand by those which can be tolerated.

Certain apparent discrepancies between some of the smaller values are due to the fact that all amounts have been rounded off to the nearest 0·00005 in.

Screw Thread Limit Gauges. In Fig. 108 are shown plug and ring gauges for use in testing internal or external threads. Such gauges are,

clearly, comparable with those discussed in Chapter VIII and shown in Fig. 77 for use as standards in the measurement of internal and external plain diameters.

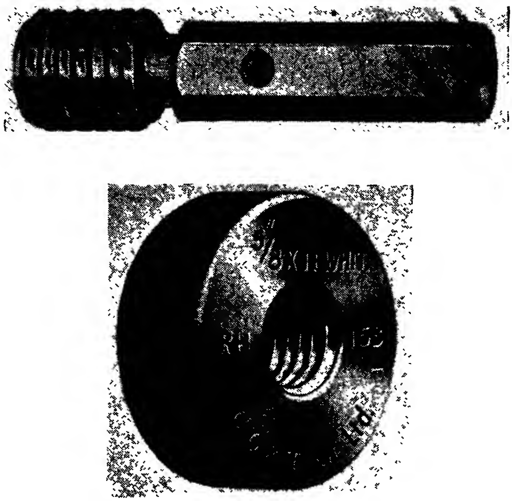


Fig. 108. Thread Plug and Ring Gauge

TABLE XXII

Whitworth Threads

Effect of Angular Error on Effective Diameter

Total Angular Error $(a_1 + a_2)$	Threads per inch					
	4·5	7	10	14	20	26
0·1	0·00025	0·00015	0·00010	0·00010		
0·5	0·00115	0·00075	0·00050	0·00040	0·00025	0·00020
1·0	0·00230	0·00150	0·00105	0·00075	0·00050	0·00040
1·5		0·00225	0·00155	0·00120	0·00080	0·00060
2·0			0·00210	0·00150	0·00105	0·00080
3·0				0·00225	0·00150	0·00120
4·0					0·00210	0·00160
5·0						0·00200

N.B. The error should be "added" for external and "subtracted" for internal threads.

TABLE XXIII

B.A. Threads

Effect of Angular Error on Effective Diameter

Total Angular Error ($a_1 + a_2$)	Designating Number					
	0	3	5	8	10	12
0·3	0·00010	0·00010				
0·5	0·00020	0·00015	0·00010	0·00010		
1·0	0·00035	0·00025	0·00020	0·00015	0·00010	0·00010
2·0	0·00070	0·00050	0·00040	0·00030	0·00025	0·00020
4·0	0·00145	0·00105	0·00085	0·00060	0·00050	0·00040
6·0	0·00215	0·00155	0·00125	0·00090	0·00075	0·00060
8·0		0·00210	0·00170	0·00125	0·00100	0·00080
10·0			0·00210	0·00155	0·00125	0·00100

N.B. The error should be "added" for external and "subtracted" for internal threads.

TABLE XXIV

U.S. and other 60° Threads

Effect of Angular Error on Effective Diameter

Total Angular Error ($a_1 + a_2$)	Threads per inch					
	4·5	8	10	14	20	28
0·1	0·00030	0·00015	0·00015	0·00010		
0·5	0·00145	0·00080	0·00065	0·00045	0·00035	0·00025
1·0	0·00290	0·00165	0·00130	0·00095	0·00065	0·00045
1·5		0·00250	0·00195	0·00140	0·00100	0·00070
2·0			0·00260	0·00185	0·00130	0·00095
3·0				0·00280	0·00195	0·00140
4·0					0·00260	0·00185
5·0						0·00235

N.B. The error should be "added" for external and "subtracted" for internal threads.

Whilst such gauges are, perhaps, those most frequently met, they are clearly not suited to "limit" gauging. For this purpose "go" and "not go" gauges for threaded holes take forms similar to those shown

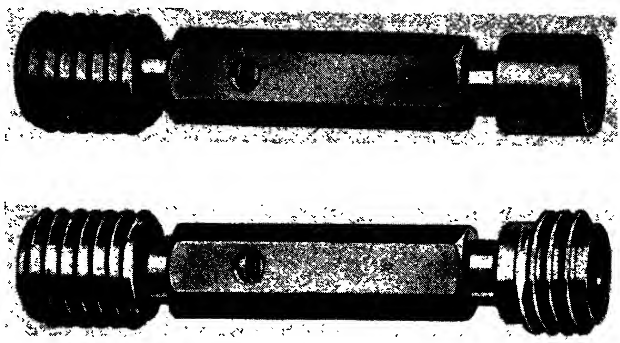


FIG. 109. THREAD LIMIT GAUGES

in Fig. 109, which are types manufactured by the Coventry Gauge & Tool Company. The upper gauge in the illustration has on its left-hand end a threaded plug made to full plan form of the thread in question. It is designed to be just below the low limit, so that it is a "go" gauge and takes into account errors of pitch or of flank angle. The right-hand end is intended to gauge the crests of the threads, and may be either the "go" or the "not go" limit.

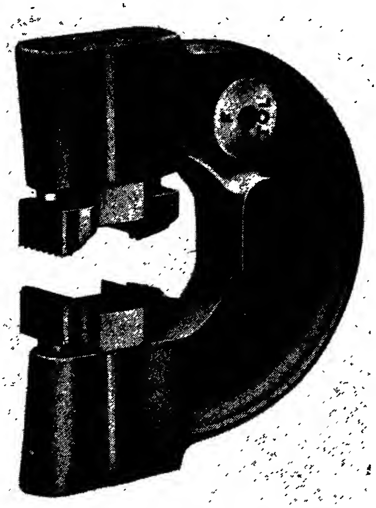


FIG. 110. WICKMAN LIMIT GAUGE

The lower gauge in the illustration has on its left-hand end a full-form "go" thread, whilst on its right-hand end it carries the "not go" thread. It will be seen that this latter consists of only a few (not more than three) threads and the crests are truncated. This is a test of the true effective diameter without taking into account errors of pitch or flank angle.

For the limit gauging of external threads Fig. 110 shows a Wickman type gauge with adjustable anvils. This is a type used for "go" and

"not go" inspection, the anvils being adjusted by means of plug thread standards of the appropriate "go" and "not go" sizes.

As in the case of the screw plug gauges, the front anvils are of full form, and thus ensure not only that the crest and root diameters are not over size, but also that the effective diameter, both in itself and taking into account errors of pitch and angle, is not excessive. The rear anvils are truncated and consist of only a few threads, since their purpose is to ensure that the simple effective diameter (i.e. excluding errors of pitch and angle) is not under size.

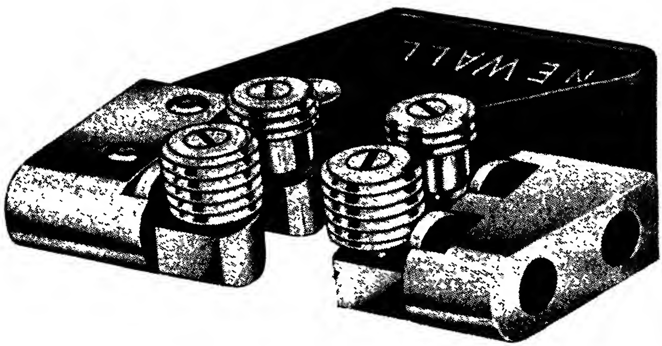


FIG. 111. ROLLER LIMIT GAUGE

Fig. 111 shows a roller type of gauge as manufactured by Messrs. Newall. This uses rollers instead of the fixed type of anvil used in the Wickman gauge, and it is claimed that this entails far less wear. The rear rollers are truncated and contain only a few threads. It will be noted that in the type shown the rollers are capable of being used to test a thread right up to a shoulder. Whilst these present some advantages over the Wickman type where repeated and rapid inspection is concerned, it is probable that the latter is, on the whole, the more accurate.

In the inspection of screw threads the following are recommended—

For Internal Threads

1. "Go" screw plug. This is of full form and possesses a length of thread corresponding to the normal length of engagement.

2. "Not go" screw plug. This has only three threads whose crests are truncated and whose roots are cleared so as to engage only at the effective diameter.

3. "Not go" plain plug.* This is made to the maximum diameter of the root of the nut thread.

For External Threads

1. "Go" screw calliper or ring. This is of full form and possesses a length of thread corresponding to the normal length of engagement.

2. "Not go" screw calliper. (Ring screw gauges are *not* used for "not go" purposes.) The gauge has only three threads whose crests are truncated and whose roots are cleared so as to engage only at the effective diameter.

3. "Not go" plain gap.* This is made to the minimum diameter of the crest of the bolt thread.

Thread Gauge Limits. We have, in the foregoing, seen the main points which screw thread gauges are designed to check. The tolerances which are permitted and the disposition of these tolerances follow principles similar to those which govern the limits set to plain plug and ring gauges, as discussed in Chapter VIII.

It will be noted that with plug "go" gauges a departure has been made in the manner of specifying the effective diameter in that equivalent errors due to errors of pitch and thread angle are given separately. This permits the gauge manufacturer more latitude, since otherwise there was a tendency to keep the effective diameter at the lower limit in order to allow room for the other errors. This necessarily shortened the life of the gauge.

We have already seen that "go" gauges should possess the standard form of thread and a number of threads corresponding to the normal length of engagement. "Not go" gauges are cleared at the crests and roots, and bear on the flanks only for a short length either side of the effective diameter. They possess a maximum of three threads.

Tables XXV and XXVI show the limits permitted on the various classes of gauges. It will be noted that no distinction is made between "Inspection" and "Workshop" for "not go" gauges. This was in order that the numbers of gauges required in war-time might be kept to a minimum. It will be appreciated that, with a "not go" gauge made to "Inspection" limits, any wear which takes place will render it more, not less, suitable as a "Workshop" gauge. Tolerances for "Reference" gauges have not been given, but in general these may be said to be approximately half those permitted to "Inspection" gauges.

* Although only "not go" plain plug and gap gauges are recommended for use with Whitworth threads it is an advantage to have "go" plain gauges also, and these are definitely recommended in the case of S.I. threads.

The tables apply primarily to Whitworth and B.A. (down to No. 7) type threads, but may also be used for those of metric form.

TABLE XXV*

LIMITS FOR SCREW THREAD PLUG GAUGES (INCH UNITS)

Size	Part	Limits "Go" Gauge		Limits "Not go" Gauge	Plain Plug "Not go"
		Workshop	Inspection	Inspection	Inspection
0 to 1·5 in.	Crest diameter	+ 0·0006 − 0	+ 0 − 0·0006		
	Effective diameter	+ 0·0006 + 0·0002	+ 0 − 0·0004	+ 0·0004 − 0	+ 0·0003
	Pitch and angle effect	0·0005	0·0005	0·0003	− 0
	Root diameter	+ 0·0006 − 0·0004	+ 0 − 0·0010		
1·5 in. to 3·0 in.	Crest diameter	+ 0·0009 − 0	+ 0 − 0·0009		
	Effective diameter	+ 0·0009 + 0·0003	+ 0 − 0·0006	+ 0·0006 − 0	+ 0·0004
	Pitch and angle effect	0·0006	0·0006	0·0003	− 0
	Root diameter	+ 0·0009 − 0·0006	+ 0 − 0·0015		
3·0 in. to 6·0 in.	Crest diameter	+ 0·0014 − 0	+ 0 − 0·0014		
	Effective diameter	+ 0·0014 + 0·0006	+ 0 − 0·0008	+ 0·0008 − 0	+ 0·0005
	Pitch and angle effect	0·0008	0·0008	0·0004	− 0
	Root diameter	+ 0·0014 − 0·0007	+ 0 − 0·0021		

Micrometer Screw Plug Gauge. For making measurement of actual thread dimensions in holes the instrument illustrated in Fig. 112, made by the Coventry Gauge & Tool Company, may be employed. Such gauges are obtainable in a wide range of sizes.

* Abstracted from B.S. 919, "Screw Thread Gauge Tolerances," by permission of the British Standards Institution, from whom official copies of the specification may be obtained, price 2s. 3d. post free.

TABLE XXVI*

LIMITS FOR SCREW THREAD RING OR GAP GAUGES (INCH UNITS)

Size	Part	Limits "Go" Gauge		Limits "Not go" Gauge	Plain Gap "Not go"
		Workshop	Inspection	Inspection	Inspection
0 to 1·5 in.	Root diameter	+ 0·0003 − 0·0006	+ 0·0009 − 0		
	Effective diameter	+ 0 − 0·0006	+ 0·0006 − 0	+ 0 − 0·0003	+ 0 − 0·0003
	Crest diameter	+ 0 − 0·0006	+ 0·0006 − 0		
1·5 in. to 3·0 in.	Root diameter	+ 0·0005 − 0·0009	+ 0·0014 − 0		
	Effective diameter	+ 0 − 0·0009	+ 0·0009 − 0	+ 0 − 0·0005	+ 0 − 0·0004
	Crest diameter	+ 0 − 0·0009	+ 0·0009 − 0		
3·0 in. to 6·0 in.	Root diameter	+ 0·0007 − 0·0014	+ 0·0021 − 0		
	Effective diameter	+ 0 − 0·0014	+ 0·0014 − 0	+ 0 − 0·0007	+ 0 − 0·0005
	Crest diameter	+ 0 − 0·0014	+ 0·0014 − 0		

N.B. "Not go" gauges of the ring type should not be employed.

One end of the tubular body is slotted to take three thread-ground jaws, which bear, on their inner faces, against a central cone capable of being moved axially by the micrometer head. Contact is maintained by three semi-elliptic springs. The thimble is graduated in steps of 0·0001 in., and it is possible to "feel" to the nearest 0·0001 in. A screwed gauge ring is supplied to enable the zero setting to be checked and adjusted from time to time. In use, the instrument is screwed into the hole, adjusted to below normal size, and the measurement is then made. After this it is once again adjusted to below size before unscrewing.

Pitch Measuring Machine. The pitch measuring machine shown in Fig. 113 is made by the Coventry Gauge & Tool Company. It is

* Abstracted from B.S. 919, "Screw Thread Gauge Tolerances," by permission of the British Standards Institution, from whom official copies of the specification may be obtained, price 2s. 3d. post free.

designed to make accurate measurement of the pitch of internal or external threads, whether parallel or taper.

The work is held rigidly in the machine and a suitably shaped stylus bears on the thread. This stylus is carried in a saddle which

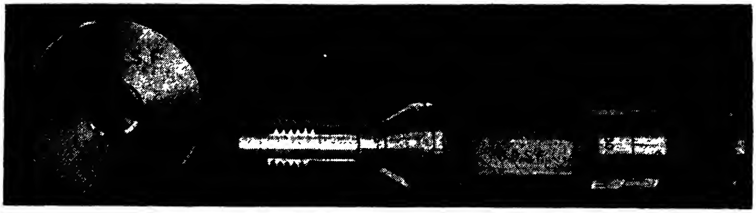


FIG. 112. MICROMETER PLUG GAUGE

may be traversed by means of an accurate lead screw operated by the micrometer head. As the stylus is drawn along the thread parallel to the axis it rides in and out and, through a series of levers, operates a

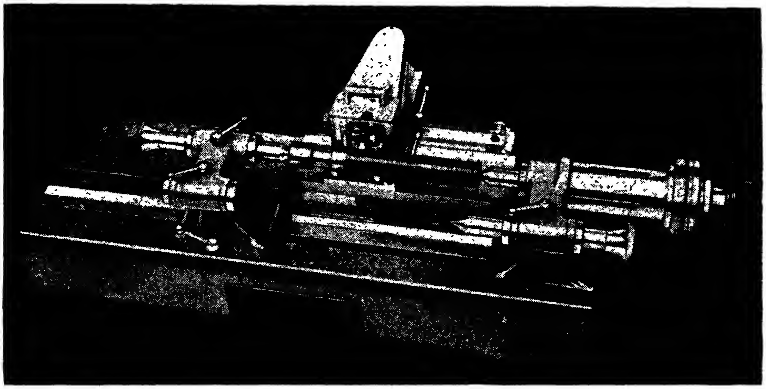


FIG. 113. PITCH MEASURING MACHINE

fiducial indicator. If this be adjusted initially so that it reads zero when the stylus bears on both flanks of a thread, it is a simple matter to read from the micrometer the distance to the next similar reading.

The micrometer head may be fitted with a disc so that graduations represent 0·0001 in. Alternatively, other discs may be used with graduations suited to the number of threads per inch of the screw being measured. Readings repeat to within 0·000025 in. The lead screw is calibrated and provided with a corrector bar of the conventional type so that errors due to it should be minute.

Diameter Measuring Machine. This machine was described in detail in Chapter VIII, and Fig. 82 shows a close up of an external thread diameter being measured by means of suitable wires or cylinders. It is clear that it is in the highest degree important that the cylinders used should be truly circular in section, and that their diameters should be accurately known. The actual diameter, furthermore, should be carefully chosen. Theoretically, it should be such that the points of contact with the flanks lie on the effective diameter. In practice, however, this would demand an enormous number of standard sizes for cylinders and it has been agreed that it is satisfactory for the cylinder to touch inside the middle tenth of the straight length of the flank. With this latitude contributory errors due to errors of flank angle within the permitted tolerance are negligible when determining the effective diameter. Suitable sizes for cylinders fulfilling the above conditions are set out in Table XXVII.

TABLE XXVII

SCHEDULE OF SIZES FOR THREAD-MEASURING CYLINDERS

Cylinders Marked	Suitable for Threads			Limits on Diameter of Cylinders inches
	Whitworth (55°) t.p.i.	Metric (60°) Pitch mm.	B.A. (47½°)	
3 Whit.	3	8	—	0·184 to 0·190
3¼ ,,	3¼	7·5	—	0·170 to 0·176
3½ ,,	3½	7	—	0·158 to 0·164
4 ,,	4	6·5 and 6	—	0·139 to 0·145
4½ ,,	4½	5·5	—	0·122 to 0·128
5 ,,	5	5 and 4·5	—	0·107 to 0·110
6 ,,	6	4	—	0·090 to 0·096
7 ,,	7	3·5	—	0·078 to 0·084
8 ,,	8	3	—	0·067 to 0·073
9 ,,	9	2·75	—	0·059 5 to 0·066
10 ,,	10	2·5	—	0·053 5 to 0·059 5
11 ,,	11	2·25	—	0·048 5 to 0·054
12 ,,	12	2	—	0·044 5 to 0·049
14 ,,	14	1·75	—	0·038 to 0·042 5
16 ,,	16	1·5	—	0·033 5 to 0·036 5
18 ,,	18 and 19	—	—	0·029 8 to 0·031 2
20 ,,	20	1·25	—	0·026 7 to 0·029 7
22 ,,	22	—	—	0·024 3 to 0·026 9
24 ,,	24	—	—	0·022 3 to 0·024 7
26 ,,	26	1	No. 0	0·021 0 to 0·022 2
28 ,,	28 and 30	—	No. 1	0·019 1 to 0·019 8
32 ,,	32	0·75	No. 2	0·016 8 to 0·018 0
34 ,,	34 and 36	—	No. 3	0·015 7 to 0·016 3
40 ,,	40	—	No. 4	0·013 7 to 0·014 7
5 B.A.	—	—	No. 5	0·012 2 to 0·013 2
48 Whit.	48	0·5	No. 6	0·011 1 to 0·011 8
7 B.A.	—	—	No. 7	0·009 9 to 0·010 7
8 B.A.	—	—	No. 8	0·008 9 to 0·009 5
9 B.A.	—	—	No. 9	0·008 1 to 0·008 7
10 B.A.	—	—	No. 10	0·007 2 to 0·007 8

The formula for calculating the effective diameter is—

$$E = T + P - C$$

where E = effective diameter.

T = dimension between measuring anvils when bearing on cylinders.

$P = \frac{1}{2}p \cot \theta - (\operatorname{cosec} \theta - 1)d$.

c = correction due to tilt of cylinder on account of rake.

θ = half angle of thread.

p = pitch.

Values of P are—

Whitworth	$(\theta = 27\frac{1}{2}°)$	$P = 0{\cdot}96049p - 1{\cdot}16568d$
B.A.	$(\theta = 23\frac{3}{4}°)$	$P = 1{\cdot}13634p - 1{\cdot}48295d$
B.S.F. (or C.E.I.), U.S., S.I.	$(\theta = 30°)$	$P = 0{\cdot}86602p - d$

The values for c can be found in appropriate tables. For B.S.W. threads it is of the order of 0·00015. For B.S.F. threads it is approximately 0·0001 or less. For B.A. screws it lies between 0·00005 and 0·00007.

Fig. 114 illustrates an ingenious development of the cylinder method of measuring effective diameter. These gauges are known as O-Vee thread-measuring gauges and are produced by Messrs. J. E. Baty & Co. As may be seen, they are self-supporting in the threads, and any normal means of making the actual measurement may be employed.

It is important to remember that the amount of pressure applied will have an appreciable effect upon the reading which is obtained. The amount of this effect is clearly dependent upon the size of the thread being measured and upon the pressure which is applied. About half the error can be eliminated if a measurement is first made upon a plain plug whose diameter is accurately known, providing that precautions are taken to apply the same pressure to the micrometer in each case. With screws whose diameter is less than about $\frac{1}{4}$ in. the amount of correction to be applied is from 0·0001 in. to 0·0002 in., and it is clear that this assumes an importance in the case of the smaller

B.A. sizes of screws. With the Whitworth type of thread the corrections are smaller and do not amount to much more than half those with B.A. threads.

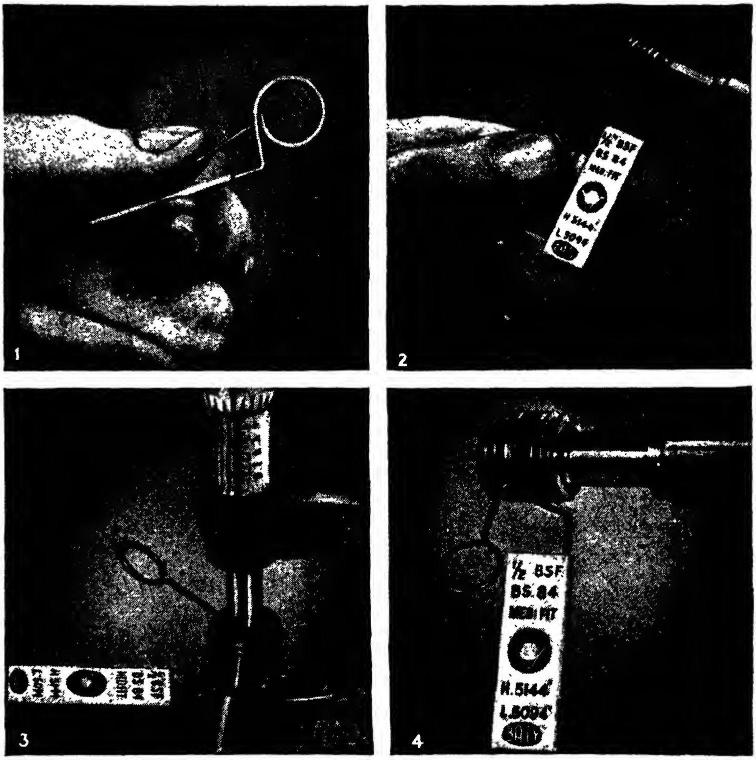


FIG. 114. "OVEE" THREAD MEASURING WIRES

The *root* diameter of an external thread may be measured by aid of suitable wedges whose angle is less than that of the thread.

Details of an internal thread may be measured to a fairly close degree of accuracy by taking a plaster cast of the thread and making measurements on the cast.

CHAPTER XI

U.S.A. MEASURING INSTRUMENTS

It would clearly be quite impossible in the space of a single chapter to do justice to the whole range of inspection instruments manufactured in the U.S.A.; but the following is intended to give a necessarily brief but representative description of a very few of them.

General Purpose Instruments. Since such testing appliances as callipers, micrometers, dial gauges, slip gauges, height gauges, depth gauges, plug and ring gauges (both plain and thread), etc., have been described in their appropriate places in the foregoing chapters it is unnecessary to describe again in detail the same types of instruments as produced in the U.S.A. Suffice it to say that all these various classes of instruments are manufactured in the United States, and many of them may be obtained in Great Britain through the appropriate agents. Firms specializing in this class of work include, amongst many others, the following—

B. C. Ames Co., Waltham, Mass.
Brown & Sharpe Mfg. Co., Providence, Rhode Island.
Cadillac Gage Co., Detroit, Mich.
Jansson Gage Co., Farmington, Mich.
Phoenix Gage Co., Phoenix, N.Y.
Starrett Co., Athol, Mass.
Taft-Peirce Mfg. Co., Woonsocket, Rhode Island.
Vinco Corporation, Detroit, Mass.

A few special purpose instruments selected from a very wide range, as examples only, are described below.

Toolmaker's Microscope (Bausch & Lomb). This is very similar to the instrument which has already been described in Chapter VI and illustrated in Figs. 29 and 30. It is shown in Fig. 115, and the protractor eye-piece, which is a separate attachment, is in position.

The object to be examined may be either opaque or transparent. The object table is controlled by two micrometer screws which read to an accuracy of 0·0001 in. and give a travel of 1 in. The image is correctly shown in the field of view so that objects and movements are presented in their natural aspect, not reversed as in an ordinary microscope.

In using this, as indeed in using any other type of measuring microscope, monochromatic artificial light is to be preferred to daylight even though the latter be filtered.

When used with a 32 mm. objective the magnification is 42 ×, whilst with a 48 mm. objective the magnification is 21·5 ×. Other

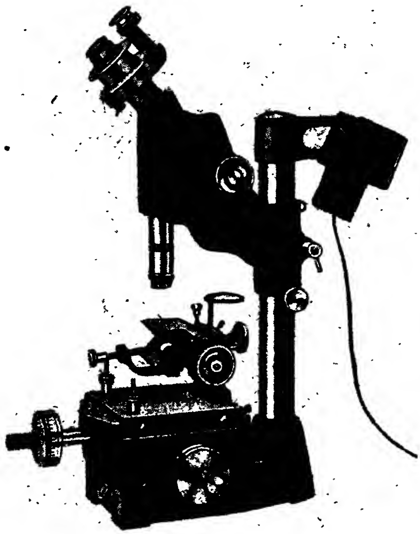


FIG. 115. TOOLMAKER'S MICROSCOPE
(*Bausch & Lomb*)

magnifications may be obtained by the use of other objectives and eye-pieces.

Optical Projector (Jones & Lamson). This instrument is sold under the name of the J. & L. Pedestal Comparator and Measuring Machine. The work platform and viewing screen are shown in Fig. 116. A threaded drum is under examination.

The instrument may be used under normal shop lighting conditions. Either of two types of work table may be used, the one having a 4 in. and the other having an 8 in. travel. The table base is supplied with two 1 in. micrometers graduated in either 0·0005 in. or 0·0001 in. (Alternatively metric instruments may be obtained graduated to 0·01 mm. or 0·005 mm.) The normal magnification of the image as seen on the screen is 62½ times.

To make lateral measurements the procedure is similar to that employed with a measuring microscope. The shadow of one of the limits of the work (say the flank of a thread) is aligned with a master mark or outline on the chart or screen. Measuring "slips" or blocks of the appropriate size and an end measuring micrometer are put into

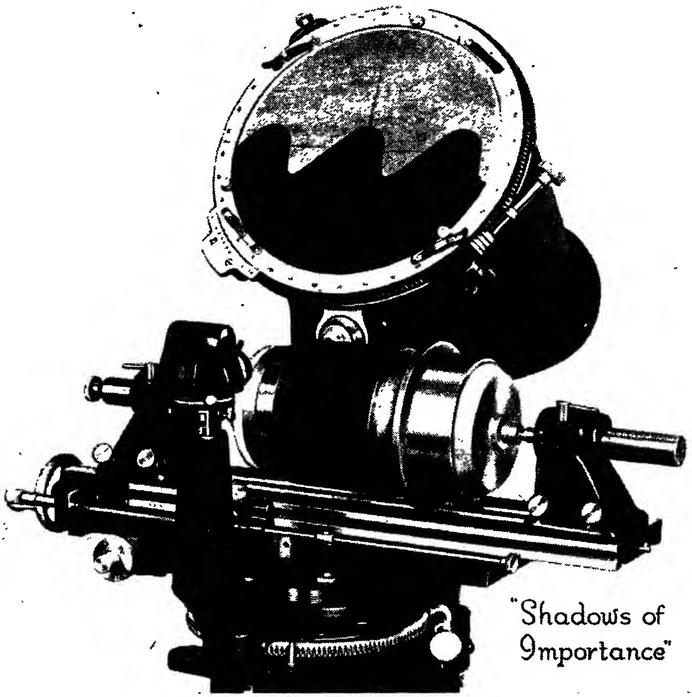


FIG. 116. OPTICAL PROJECTOR
(*Jones & Lamson*)

place and the micrometer dial adjusted to zero. The table is moved to bring against the master mark the next limit of the work (say the flank of the next thread) and the amount of movement noted on the dial or else by the addition or subtraction of measuring blocks in conjunction with the dial reading. If a block of the exact plan size of the dimension being measured is available the dial will indicate the "error."

Vertical measurements may be made in a somewhat similar manner. The vertical operating handwheel operates as a nut on an accurately ground thread spindle, the pitch being 0·125 in. (or 3 mm. when

metrically graduated). The handwheel is suitably graduated so that readings of 0·0001 in. or 0·005 mm. may be made.

Angular measurements may be made by rotating the screen holding attachment. When making measurement of flank angles of worm threads, etc., a correction is required, since the actual flank angle differs slightly from that of the shadow. Suitable tables are provided.

Bench Micrometer (Van Keuren). This instrument, which is illus-

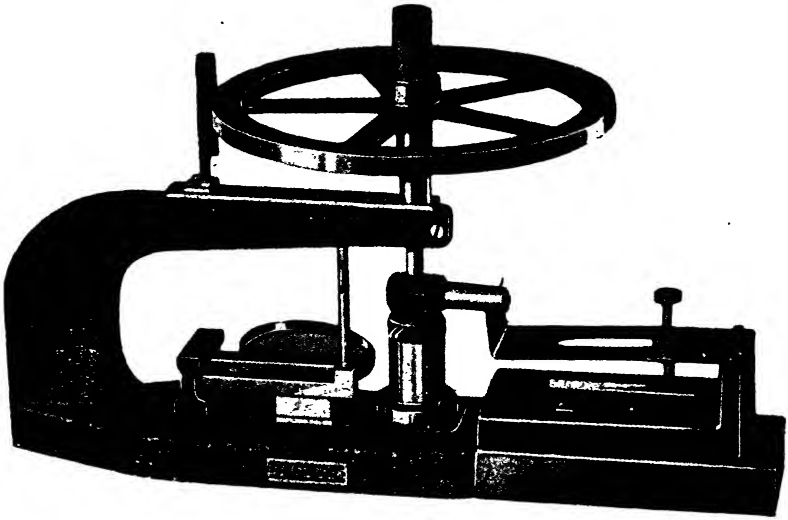


FIG. 117. BENCH MICROMETER
(*Van Keuren*)

trated in Fig. 117, is a robust micrometer of the normal bench type, with a large-diameter head permitting wide graduations. The micrometer screw of each instrument is calibrated, and a chart is provided showing corrections to 0·00001 in.

An ingenious and unusual feature is the employment of a simple optical system to indicate the degree of pressure which is being applied by the micrometer screw. By this means it is possible to control the pressure to a very close degree, and it is claimed that readings may be duplicated by different workers as closely as 0·00001 in.

Electric Comparator (Metron Instrument Co.). This instrument operates as a normal comparator and is provided with a scale giving plus and minus readings. The length of the scale is 2 in. on each side of zero (total length 4 in.) divided into divisions of 0·1 in. Four sensitivities are possible with each instrument as follows—

Range	0·1 in. of scale represents
± 0·0002 in.	0·00001 in.
± 0·0004 ,,	0·00002 ,,
± 0·002 ,,	0·0001 ,,
± 0·002 ,,	0·0002 ,,

The spindle pressure is adjustable from 2 oz. to 2 lb., and once set remains essentially constant.

In its principle of action this instrument differs fundamentally from those of an optical or mechanical type in that it is electro-mechanical in operation. The head contains a symmetrical inductance bridge network so arranged that a minute motion of the plunger moves an armature, thus providing an unbalance in the bridge. The degree of unbalance is shown by the electrical indicator whose scale has been described above. The four ranges are obtained by means of a simple switching device.

The gauge head may be revolved in the vertical plane to any angle (which can be read on the protractor) and locked in that position. It may also be swivelled around the column. (See Fig. 118.)

Sheffield Comparator (Sheffield Gauge Corporation). This comparator is supplied in a variety of different types, all of which, however, operate on the same principle, which has many novel features.

In essence the measured "error," as determined by the movement of the plunger, is the relative movement between two blocks, one of which is rigidly fixed to the frame and the other to the plunger. The blocks are connected together by means of metal reeds whose relative movement is very highly magnified. This essential mechanism is illustrated in Fig. 119. The fixed and moving blocks are connected together horizontally by means of metal strips or reeds which permit relative vertical, but not horizontal movement. The contact point and spindle form an integral part with the moving block. Vertical metal strips or reeds are attached close together to the top sides of the two blocks and their top ends rigidly joined together. This top joint is prolonged to a pointer or target.

Any movement of the contact point up or down causes the two vertical reeds to attempt to slip past one another; but, as they are joined together at their upper ends, the resultant movement is that the top swings over in an arc, which swing is amplified in distance at the far end of the pointer. This far end, or target, is projected by an optical

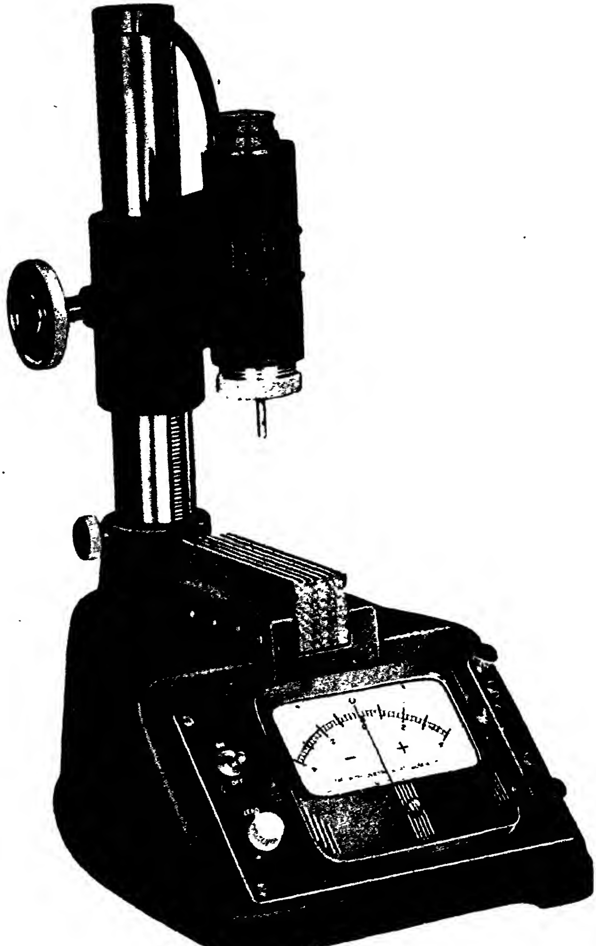


FIG. 118. ELECTRIC COMPARATOR
(*Metron*)

system on to the scale, so that a further magnification is obtained. Standard magnifications range from 500 to 10,000 with capacities of 6 in. in the lower magnification instruments and $4\frac{1}{4}$ in. in the higher. In the highest magnification each scale graduation represents

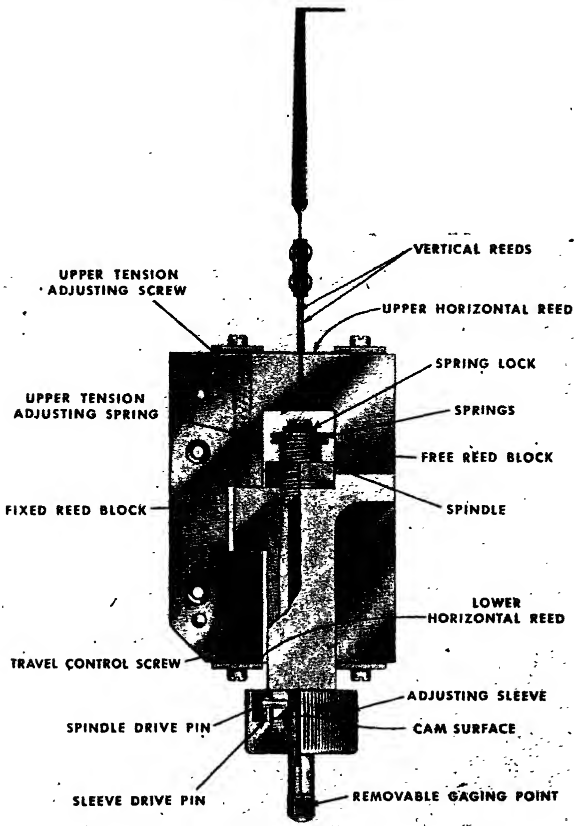


FIG. 119. VISUAL GAUGE MECHANISM
(*Sheffield*)

0·00001 in. The scale is 5 in. long, with a total range of 0·0005 in. (See Fig. 120.)

It is claimed that operators using hand loading can classify components to "half a tenth" at rates of more than 3000 an hour. Another variety of this comparator may be obtained in which the error is not indicated but in which an electric light signals "pass" or "not pass."

Involute Measuring Machine (Fellows). The main point about this

instrument is that, unlike most involute testing machines, it does not depend upon rolling round a base circle. Whilst otherwise an excellent test, the "base roll" method demands a different diameter roll for every different gear diameter. The new Fellows machine depends only upon

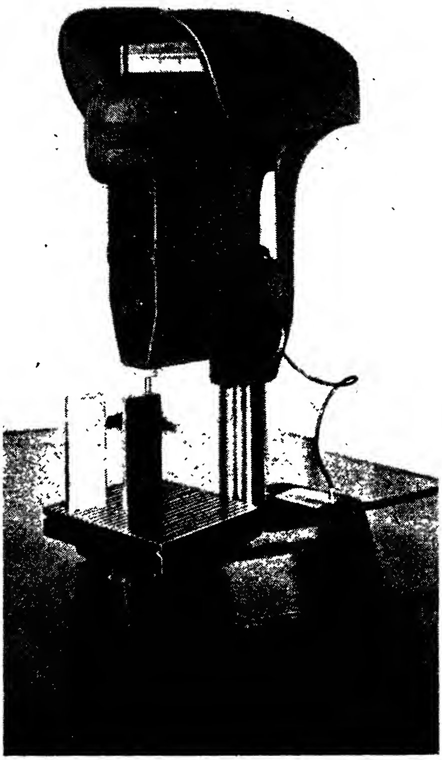


Fig. 120. Visual Gauge
(*Sheffield*)

a master involute cam whose size is independent of the diameter of the base circle. The system of setting automatically locates the pointer at the correct base circle radius.

Provision is made for withdrawing the pointer and re-inserting it when passing from tooth to tooth. To deal with those cases where there is a deliberate departure from the true involute there is a graduated dial which moves with the work, and which, in conjunction with

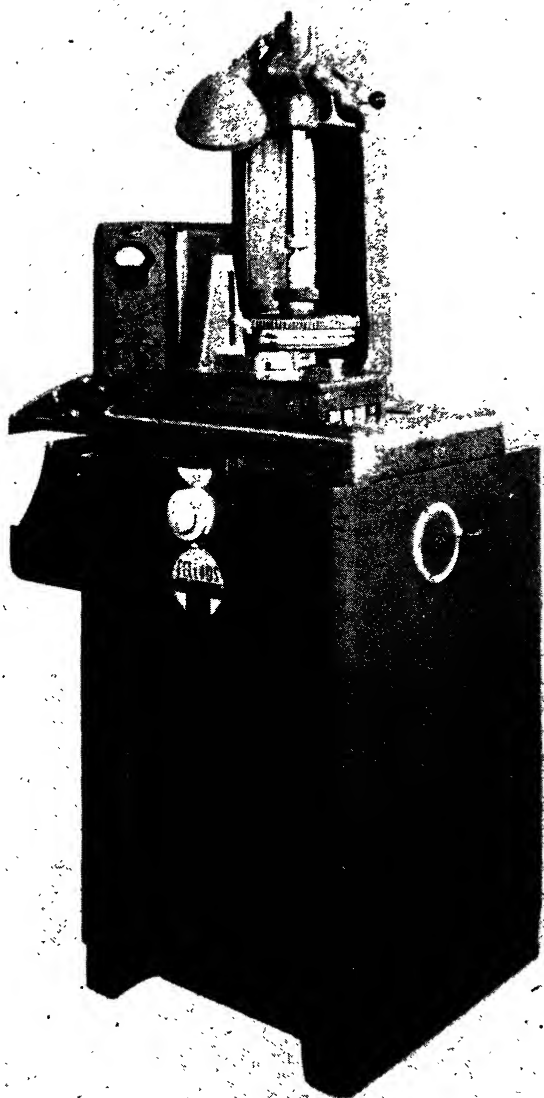


FIG. 121. INVOLUTE TESTER
(*Fellows*)

the dial indicator, indicates the amount and angular position of the modification. The instrument is illustrated in Fig. 121.

Gear Testers (Fellows). In addition to the involute tester described above, the Fellows Gear Shaper Company produce a very wide range

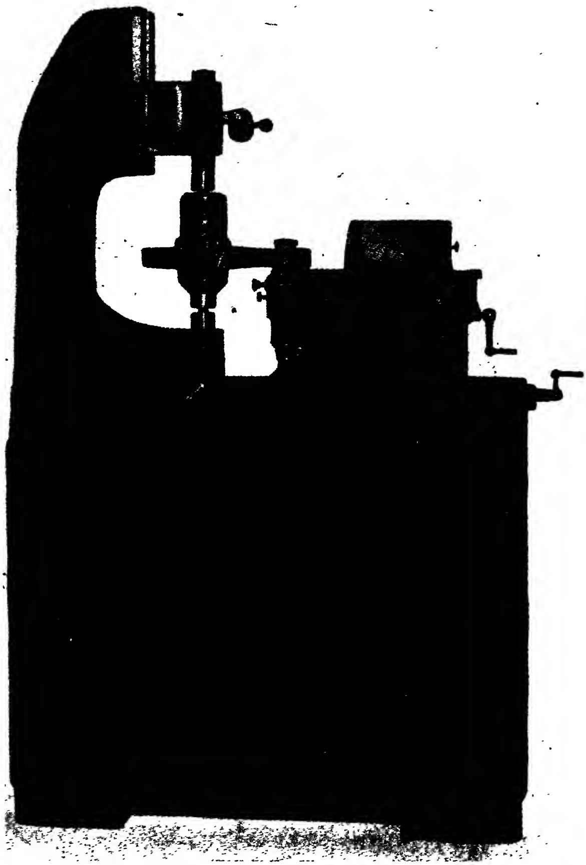


FIG. 122. "20 M" TESTER
(Fellows)

of gear testers. Figs. 122 and 123 show respectively a full view and a close-up of one of the instruments in this range. This is known as the No. 20M "Red Liner," and is capable of handling work on centres up to 18 in. pitch diameter.

The work to be tested is held between centres or on an arbor, as

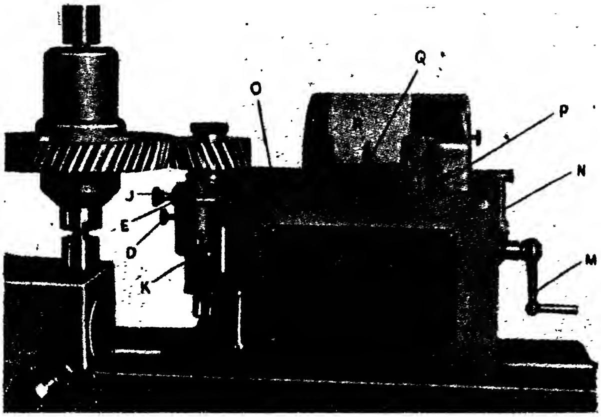


FIG. 123. "20 M" TESTER (CLOSE VIEW)

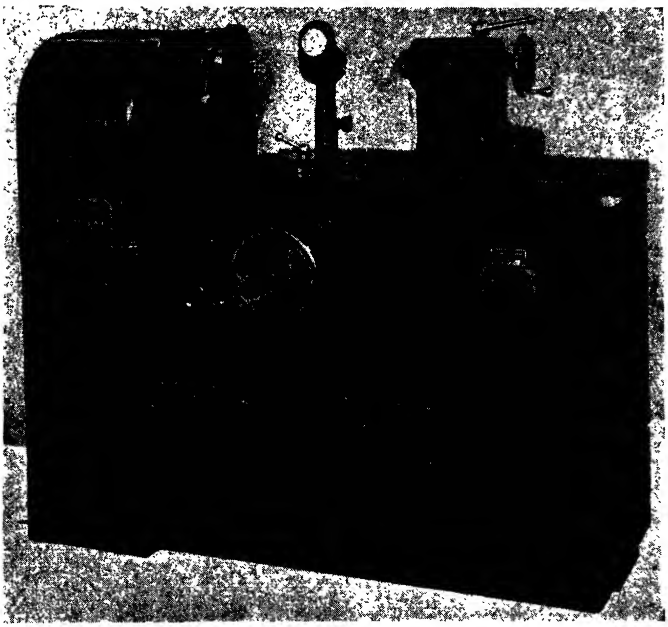


FIG. 124. GEAR TESTER
(*Michigan*)

shown on the left of the figure. The centres are, of course, accurately aligned and adjustable as to distance apart. The cabinet carrying the master gear and the mechanism and paper for obtaining a graphical record is shown on the right of Fig. 122 and in the close-up, Fig. 123. Records are produced in the form of red lines on the chart (hence the

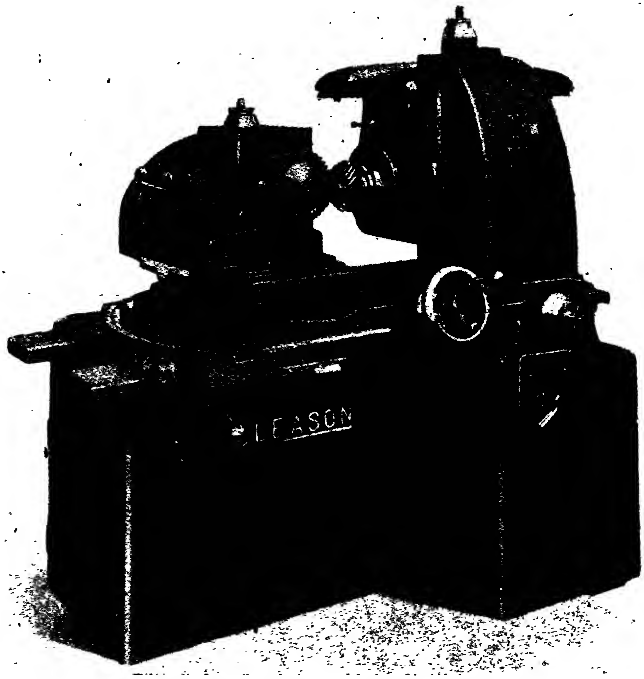


FIG. 125. BEVEL TESTER
(*Gleason*)

name), and suitable analysis yields information as to such errors as eccentricity, irregular tooth spacing or profile, interference, lack of continuous action, incorrect pressure angle, etc.

The use of the tester is not confined to external gears, but may be quite simply extended to internal ones.

Gear Testers (Michigan Tool Co.). Fig. 124 illustrates one of a range of testing machines produced by the Michigan Tool Company. It is designed to check right- and left-hand spiral gear leads from zero to infinity. The standard pattern takes gears up to 18 in. in diameter, and has a bed centre distance of 24 in.

It consists primarily of two "tables," a transverse or rotatory one on the left, and a longitudinal indicator. The transverse table carries a sine bar mechanism such that, when it is moved back or forth *across* the machine, the spindle is rotated by an amount determined by the sine bar constants.

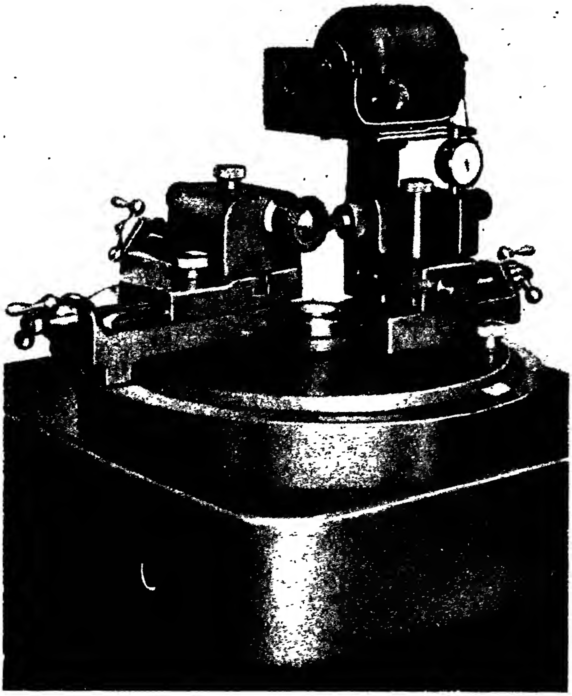


FIG. 126. HAND ROLLER
(Gleason)

Accuracy and absence of backlash are ensured by providing all spindles with pre-loaded ball bearings. The sine bar table travels on three point ball contact guides. The indicator is graduated in "ten-thousandths," and readings are readily repeated by different observers to this limit.

Bevel Gear Tester (Gleason). The underlying purpose of this machine is based upon the fact that the checking of involute tooth profiles, so commonly applied in the case of spur and helical gears, is of little value with bevel gears for two main reasons. First, the shape of a bevel gear tooth is not constant throughout its length, as is the

case with a spur gear, but varies continuously. Second, such an examination would not show the true tooth contact along the length of the tooth.

The Gleason machine is designed to give a running test under normal conditions of mounting and, if necessary, light brake load. It gives an indication of correct tooth shape, and the position of the tooth bearing may be changed by means of slight adjustments to the machine. It is thus possible to investigate how gears would operate when slightly out of position in their final mountings, and also to measure any slight changes which may be necessary in the cutting and grinding machines to provide for a satisfactory location of the tooth bearing. (See Fig. 125.)

Hand Rolling Tester (Gleason). One of these testers is illustrated in Fig. 126. Their unique feature is the pivot construction of the pinion head. The pinion spindle is permitted to move 0·01 in. either side of the centre, and is held by light spring pressure so that the gears under test are in metal-to-metal contact. As they are slowly rolled together by hand any irregularities cause slight horizontal displacements of the pinion spindle.

A small motor is provided, so that, with the pinion spindle locked in its normal position, the gears may be run together, thus (if they have been previously suitably painted) showing tooth bearing.

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